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ENGINEERING AND DEVELOPMENT PROGRAM PLAN - WAKE VORTEX.(U)
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Report No. FAA-ED-21-1A

ENGINEERING AND DEVELOPMENT PROGRAM PLAN – WAKE VORTEX

December 1977

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

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Director, Systems Research and
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16. Abstract

This Engineering and Development Program Plan defines the current research efforts investigating the wake vortex phenomenon. The overall objectives of the program are the design, development, testing, and prototyping of a system(s) to increase runway capacity by minimizing wake vortex effects as an impediment to efficient and effective traffic management in the terminal environment. The plan identifies and discusses the three major work areas: Vortex Advisory System, Wake Vortex Avoidance System, and Vortex Alleviation Research. Prior developments and related research are reviewed and future research requirements identified.

This plan supersedes Report No.: FAA-ED-21-1 dated February 1973.

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ENGINEERING AND DEVELOPMENT PROGRAM PLAN -- WAKE VORTEX

TABLE OF CONTENTS

TABLES AND FIGURES

Tables

Figures

1.0 EXECUTIVE SUMMARY

1.1 Problem Defined

Any aircraft in flight leaves in its wake two counter-rotating cylindrical air masses trailing aft from the wing, termed trailing wake vortices. With the introduction of larger transport aircraft, the wake problem takes on added significance since the increased intensity of the vortex from these aircraft can present a severe hazard to a following aircraft which encounters this wake vortex. The present solution to this problem has been to increase the interarrival separation between aircraft in the terminal area; however, this is diametrically opposed to the goal of increased airport capacity. The requirement to maintain the current extended separation standards will impede meeting the forecast traffic demands for 1980-85 and beyond, as well as causing excessive delays at currently saturated terminals during poor weather.

1.1.1. Prior Documentation

An Acquisition Paper for the Wake Vortex Program has been approved through the Advanced Development life cycle phase by the Transportation System Acquisition Review Council (TSARC) in accordance with DOT Order 4405.7, 16 January 1973. This EDPP will provide the basis for revision to the basic Acquisition Paper, Aircraft Wake Vortex Avoidance System (WVAS) (Subprogram 214-531), dated August 10, 1973. A revised Acquisition Paper (Subprogram 084-452) requesting approval through the Preliminary Operational Deployment and Demonstration phase will be submitted for TSARC review in the second quarter of Fiscal 1978.

As a supplement to the ongoing wake vortex research, the Office of Systems Engineering Management established a cost/benefit study effort for both the Vortex Advisory System (VAS) and the Wake Vortex Avoidance System (WVAS). This study was performed by Computer Sciences Corporation under contract number DOT-FA76WA-3744. The final report, Cost/Benefits and Implementation of the Wake Vortex Avoidance System (WVAS) and Vortex Advisory System (VAS) was published in September 1976. Eleven airports were considered over a ten year life cycle for both systems.

The requirements for research and development efforts in the wake vortex program are identified in FAA Report No.: FAA-EM-75-5, An Overview and Assessment of Plans and Programs for the Development of the Upgraded Third Generation Air Traffic Control System, March 1975. In this report a Wake Vortex Avoidance System was identified as one of the nine integral components of a completed

UG3rd ATC system. Specifically, the WVAS is a major contributor to system performance for increasing capacity and decreasing delay.

1.2 Background

1.2.1 Program Objectives

The overall objective of the Systems Research and Development Service Wake Vortex Program is to develop a system to provide increased airport capcity through minimization of the aircraft trailing wake vortex effect as a deterrent to efficient and effective air traffic management in the terminal airspace.

1.2.1.1 Vortex Advisory System (VAS)

The objective of the Vortex Advisory System (VAS) is to provide the air traffic controller with the criteria to reduce aircraft interarrival spacings to three nautical miles during specific meteorological conditions.

1.2.1.2 Wake Vortex Avoidance System (WVAS)

The objective of the Wake Vortex Avoidance System (WVAS) development is to design an automated system which (when integrated with the Metering and Spacing function of the Upgraded Third Generation Air Traffic Control System) will allow air traffic management utilizing dynamic interarrival spacings.

1.2.1.3 Predictive Modeling

The predictive modeling development objective is to provide the computer capability to predict all relevant factors of vortex behavior so interarrival separations can be determined based on ambient meteorological conditions and actual traffic mix.

1.2.2 Primary Areas of Research

Today there are two major approaches to the problem of minimization or elimination of the impediment on air traffic flow caused by aircraft vortices: (1) vortex alleviation and (2) avoidance.

1.2.2.1 Vortex Alleviation

The first approach involves aircraft aerodynamic modification which has potential for breaking up or minimizing the vortex more rapidly and thus providing improved safety and capacity. FAA has requested the National Aeronautics and Space Administration (NASA) to actively participate in solving the wake vortex problem. NASA has been charged with the responsibility of reviewing past and present wake vortex work to provide information on aerodynamic solutions that might accelerate vortex decay or dissipation. NASA has now completed the majority of the screening and has completed extensive testing of potential alleviation techniques. The most promising techniques have been or will, in the near future, be subjected to thorough investigation and subsequent flight test. This comprehensive testing will determine applicability of these techniques/modifications to current aircraft and future aircraft design criteria.

1.2.2.2 Vortex Avoidance

The Wake Vortex Avoidance System (WVAS) is a system of modular design which utilizes meteorological and sensor data to detect, track, and predict vortex motion and decay. Using WVAS, wind direction and speed are automatically sensed by a meteorological subsystem. This information is combined with active vortex sensor data in a digital computer-processor and then input to the Automatic Radar Terminal System metering and spacing (M+S) algorithm or displayed for the controller where it is used to determine metering and spacing commands. The combined output is then used to subsequently control aircraft arrival and departure separations.

The Vortex Advisory System (VAS), nearing the operational demonstration stage, is conceptually similar to WVAS except that the integration with the ARTS M+S algorithm and active, real-time vortex detection and tracking is not incorporated in the VAS. VAS is designed for use with manual metering and spacing and limits interarrival separations to three nautical miles.

The near term WVAS tasks include:

(a) The detailed characterization of vortices relative to transport, strength and decay through analysis of measured data with full documentation of results.

(b) The continued collection of vortex dynamics data with emphasis on providing a statistical data base on vortex strength, transport, and decay.

(c) Implementation of the meteorological-based Vortex Advisory System (VAS) at Chicago O'Hare International Airport for operational test and evaluation (O,T&E). Further implementation of the VAS at selected airports is planned in FY-79.

Long term tasks are:

(a) Development of vortex sensors and systems integration to provide real-time vortex detection and tracking.

(b) Further refinement and computer integration of a predictive model as the basis of a predictive system that will forecast vortex position in an appropriate time-frame to be used with the metering and spacing functions of the ARTS-III.

(c) Detailed design, development, and testing of a total WVAS to interface with the ARTS-III and provide tailored spacings based on both predicted and measured vortex dynamics.

(d) Identification and coordination of the interface requirements for WVAS development and the terminal automation development activities; especially to develop and test ARTS-III software to accept real-time and predictive WVAS data for integration with the metering and spacing program and controller display generation.

1.2.3 Major Decision Points

(a)	Vortex Advisory System: final Technical Reports and System Specifications submitted to Operating Services.	May 1978
(b)	Definition of system requirements for the Wake Vortex Avoidance System.	June 1978
(c)	Decision to proceed with build effort and R&D field testing of an engineering model WVAS.	July 1978

(d)	Decision on the active vortex sensing subsystem to be integrated into the WVAS.	October 1979
(e)	Definition of the predictive model for integration into the WVAS.	December 1979
(f)	Decision to proceed with the development and operational testing of a fully automated WVAS prototype.	December 1979
(g)	Determine trade-offs between alleviation (assuming successful development of an operationally viable alleviation technique) and avoidance system.	June 1980

1.3 Technical Approach

Accomplishment of the program objectives will require efforts involving detailed studies, comparative analyses, system analyses, and investigations of pertinent technology and equipment to develop a prototype WVAS system. Test equipment and fully engineered prototypes of critical systems and subsystems will be constructed and evaluated against operational requirements to ensure that hardware is within the state-of-the-art and that technical milestone schedules, performance requirements, and resource estimates for system deployment are realistic. The resulting system definition will support development and acquisition of a Wake Vortex Avoidance System to satisfactorily fulfill the forecast operational requirements.

An integrated effort will be followed in the next phase of the program which will include: (1) continued characterization of vortices through measurements and anlyses, (2) further development of sophisticated predictive models of vortex transport and decay, (3) development and integration of sensing techniques and devices to be utilized in the automated Wake Vortex Avoidance System, and (4) implementation of the first generation meteorological-based Vortex Advisory System.

1.4 Schedules and Milestones (See Figure 1-1)

1.5 Organizational Responsibilities

Under the sponsorship of the FAA, Systems Research and Development

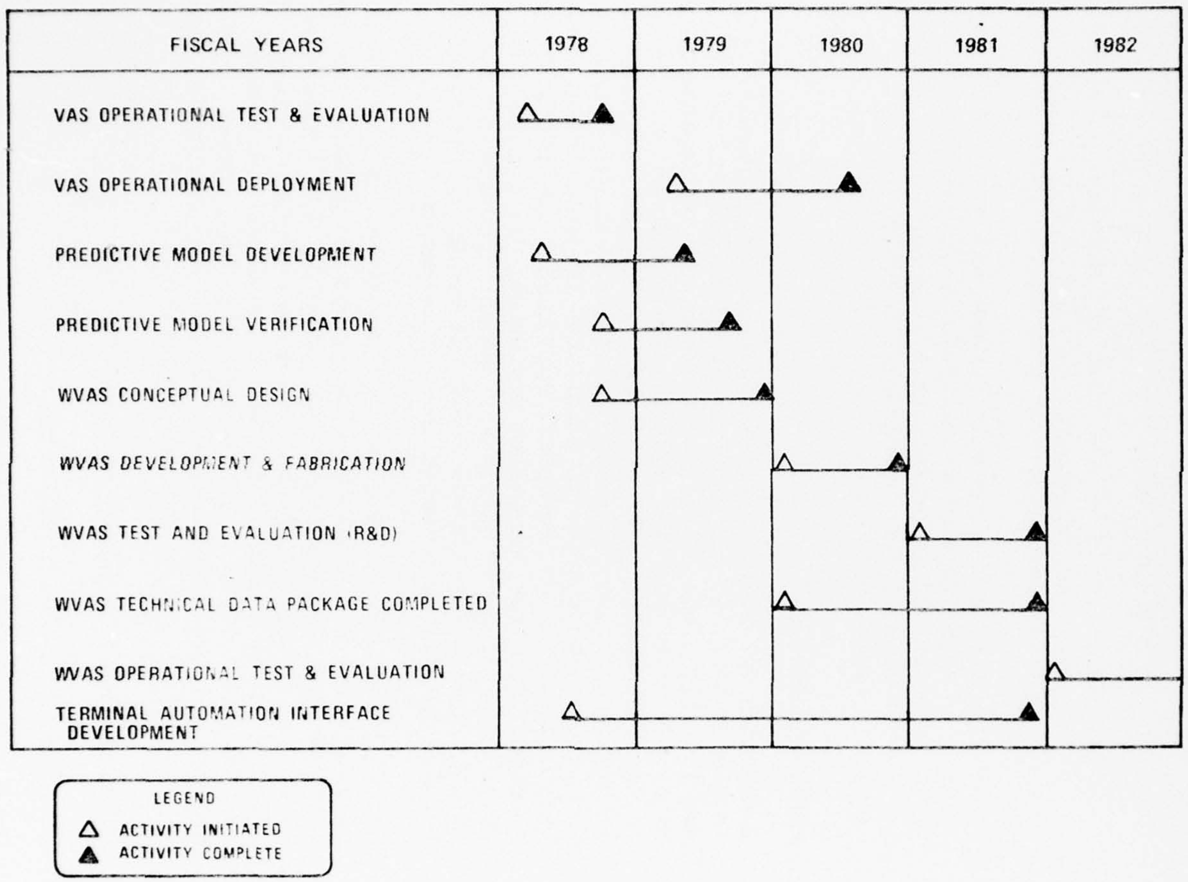

Figure 1-1. Schedule and Milestones: Wake Vortex Program.

Service (SRDS), the Transportation Systems Center (TSC) of the Department of Transportation is responsible for the wake vortex avoidance technical program design, development, and for all system design directed toward the deployment of a Wake Vortex Avoidance System (WVAS). TSC will also exercise responsibility for contracting those program elements considered necessary and within fiscal constraints by establishing work statements, initiating requests for proposals, and selecting contractors, under the fiscal direction and oversight of FAA (SRDS).

The FAA has asked the National Aeronautics and Space Administration to pursue the basic research regarding fluid dynamics of wake vortex organization, persistence and dissipation relative to the development of aircraft aerodynamic techniques to minimize or eliminate the effect of wake vortices at the source.

The FAA National Aviation Facilities Experimental Center (NAFEC) will support, as required, the operational suitability testing with associated data collection, data reduction, test reports and simulation.

1.6 Funding Requirements (See Table 1-1)

TABLE 1-1. WAKE VORTEX PROGRAM FUNDING ($000)
PROGRAM CODE: 084-452

FY 1976-1977 FUNDING:

FISCAL YEAR	1976	1976T	1977	TOTAL
IN-HOUSE	1435	299	1342	3076
CONTRACT	1013	287	330	1630
TOTALS	2448	586	1672	4706

CURRENT YEAR BREAKOUT:

FISCAL YEAR	1978					
SUBPROGRAM TITLE	W.O.		NAFEC		TSC	
	I/H	CONT.	I/H	CONT.	I/H	CONT.
VORTEX ADVISORY SYSTEM	–	125	390	–	557	50
WAKE VORTEX AVOIDANCE SYSTEM	–	–	76	–	–	175
WVAS PREDICTIVE MODELING	–	–	–	–	140	25
VORTEX ALLEVIATION RESEARCH	–	–	–	–	–	–
SUBTOTALS		125	466	–	697	250
COMBINED PROGRAM						
IN-HOUSE	1163					
CONTRACT	375					
TOTAL	1538					

FUTURE REQUIREMENTS:

FISCAL YEAR	1979	1980	1981	1982	1983	TOTAL
PROGRAM TOTALS	750	1800	1800	1000	1000	6350

NOTES: AVAILABILITY OF ESTIMATED FUNDS IS SUBJECT TO OST/OMB CONGRESSIONAL ACTIONS.
FUNDING ESTIMATES REFLECT PLANNED PROGRAM MILESTONES SUBJECT TO AVAILABILITY OF FUNDS.
CURRENT YEAR ESTIMATES ARE CONSISTENT WITH WAKE VORTEX ADVISORY/ AVOIDANCE SYSTEMS FISCAL PROGRAM.

2.0 INTRODUCTION AND BACKGROUND

2.1 Problem

A major problem facing our air transportation system is the restricted operating capacity at major U.S. air terminals, with the resulting aircraft delays, when these airports operate near their saturation point. The need to increase airport landing and takeoff capacity, under all weather conditions, without degrading current high levels of aviation safety is of prime importance to the air transportation system. Existing airport and airway system utilization is projected to increase significantly in the future. Potential capacity relief through construction of more air terminals or additional runways at existing terminals is unlikely in the current and near future economic and environmental climate.

Therefore, it is imperative that the Federal Aviation Administration (FAA) rigorously pursue an operationally viable means to increase the capacity of our present airport system.

A serious impediment to solving our capacity problem is the potential hazards caused by the aircraft vortex effect. An aircraft in flight leaves in its wake two counter-rotating cylindrical air masses trailing aft from the wing, termed trailing wake vortices. The characteristics of the wake vortex are established initially by factors related to aircraft gross weight, airspeed, flight configurations, and wingspan. Subsequently, the vortex characteristics are altered and eventually dominated by interactions between the vortices and the ambient atmosphere. Wind, wind shear, turbulence, and atmospheric stability affect the motion and demise of the vortices.

With the introduction of wide-bodied jet aircraft, coupled with the increasing number of total operations, the wake vortex problem has taken on added significance. The vortices from large aircraft can present a severe hazard to following aircraft which inadvertently encounter the vortices; i.e., the encountering aircraft can be subjected to excessive rolling moments which exceed roll control authority, a loss of altitude, or possible severe structural stress.

Thus, in the absence of an operational means to locate and track, or aerodynamically minimize wake vortices, aircraft safety is currently maintained by increasing separations between aircraft pairs to a distance which previous experience has proven is operationally safe. The requirement for increased interarrival separation is diametrically opposed to the goal of increasing airport capacity. The FAA Wake Vortex Program is directly concerned with resolving this demand-capacity-delay problem.

2.2 Program Objectives

2.2.1 General Objective

The objective of the Systems Research and Development Service Wake Vortex Program is to develop a system to provide increased airport capacity through minimization of the aircraft trailing wake vortex effect as a deterrent to efficient and effective air traffic management in the terminal airspace.

2.2.2 Specific Objectives

The FAA Wake Vortex Program is currently pursuing three basic development efforts:

(a) Vortex Advisory System (VAS)
(b) Wake Vortex Avoidance System (WVAS)
(c) Predictive Modeling

2.2.2.1 Vortex Advisory System (VAS)

The objective of the Vortex Advisory System development is to provide the air traffic controller the capability to reduce aircraft interarrival spacings to three nautical miles for all aircraft pairings during certain meteorological conditions.

2.2.2.2 Wake Vortex Avoidance System (WVAS)

The objective of the Wake Vortex Avoidance System development is to design an automated system which when integrated with the Metering and Spacing function of the Upgraded Third Generation Air Traffic Control System will allow air traffic management utilizing dynamic interarrival spacings.

2.2.2.3 Predictive Modeling

The objective of the predictive modeling development is to provide the computer capability to assess all factors of vortex behavior and status in real-time and make a valid prediction of applicable separation criteria.

2.3 Background

2.3.1 Concepts

The concept for a wake vortex advisory/avoidance system is based on three basic considerations which prior research has proven valid. These premises are:

a. Virtually all vortices move quickly off the flight path and do not constitute a hazard to aircraft following the same flight path. (Figure 2-1).

b. The duration, intensity, and movement of vortices can be predicted if adequate knowledge of the generating aircraft characteristics and the ambient meteorological conditions are known. (Figure 2-2).

c. Vortices can be detected and tracked with sensors that have been developed in earlier research and development efforts.

From the first consideration, it is evident we are penalizing airport capcity through the use of extended spacings between aircraft pairs when a majority of the time no hazard exists. The successful development of wake vortex advisory/avoidance systems will permit the "tailoring" of interarrival separation in real-time to the actual vortex condition.

The second consideration allows vortex life and movement to be predicted with sufficient accuracy to permit the adjustment of aircraft separation commensurate with the sequenced types of aircraft and the ambient meteorological conditions. These predictive techniques have been validated by the extensive vortex data which have been acquired since the inception of this program. Over 50,000 vortex pairs have been tracked and the associated vortex behavior analyzed. This analyzed data will be used to establish the parameters in the computer-based predictive model for the WVAS.

The last consideration, development of vortex sensors, has been rigorously pursued. The current generation of sensors are highly satisfactory for research and developmental testing. Further refinement and integration of sensor capability are required before a prototype wake vortex avoidance system will be ready for field testing.

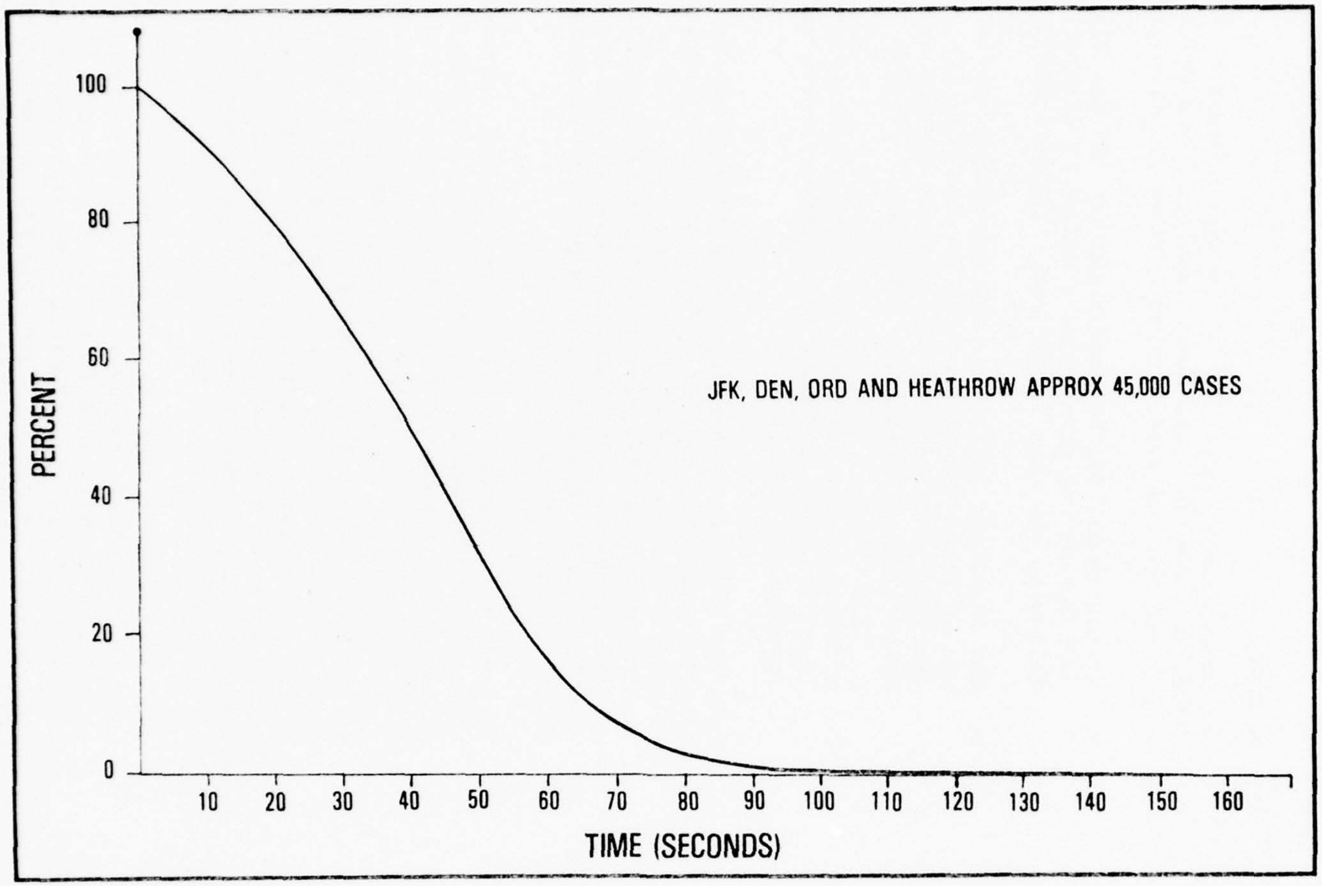

Figure 2-1. Percentage of Vortices That Linger Within a 300-Foot Window.

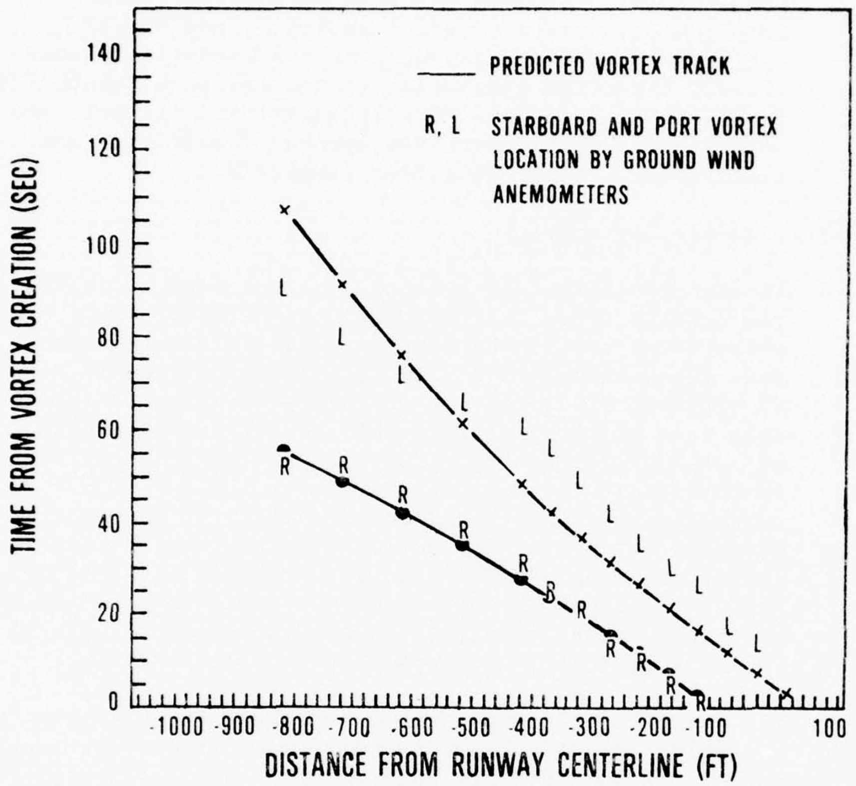

Figure 2-2. Ground Wind Vortex Track Comparison for B-747 Approach to Runway 31R at JFK.

2.3.2 Prior Developments

The initial program tasks established in this plan in February 1973 involved three major efforts: sensor development, vortex behavior analysis, and hazard definition. These tasks have been substantially completed, the first generation Vortex Advisory System (VAS) installed at Chicago O'Hare International Airport, and preliminary research and development feasibility and suitability testing have been completed.

2.3.2.1 Sensor Development

In the development of a useable vortex sensor system, researchers found that conventional detection and measurement techniques were only partially successful; thus the development of new techniques for remote sensing of of vortices was required. A vortex sensor must interact with some physical property of the vortex. The usefulness of a sensor depends upon how closely the property sensed is related to the vortex parameter to be measured. For example, smoke injected into the vortex by the generating aircraft is very useful for marking the vortex location, but it provides virtually no information on vortex strength. Therefore, the question of the appropriateness of a sensor is particularly important for the vortex sensor system which must monitor all aspects of vortex behavior.

The basic functions performed by wake vortex sensors are detection, tracking, and strength measurement (or decay). Each of these functions successively involves a higher order of complexity. Some sensors can detect and track but cannot measure strength. While trying to understand and parameterize vortex behavior, the most important vortex parameter to be measured was its strength. For those sensors which could measure strength, the detection and tracking functions were usually implemented first, before strength measurements were attempted.

Characterization of the detection function requires an understanding of miss and false-alarm rates as a function of detection threshold, vortex locations, and vortex properties. The tracking and measurement functions require establishing limits relative to accuracy. The operational usefulness of a sensor depends upon its sensitivity to operational variables such as meteorological conditions, generating aircraft type, and the presence of environmental interference.

Five general categories of sensors have been investigated: mechanical, acoustic, optical, electromagnetic, and hybrid. Extensive testing has been done with anemometers, acoustic devices, and laser equipment. Each technique offers positive features which must be considered in the final design of the operational sensor. Laser techniques, in general, provide the highest degree of overall effectiveness, but to date are the most complex and expensive.

The primary question facing research engineers in regards to vortex sensors is: Is the measurement of vortex strength an absolute requirement for an effective vortex avoidance system? If strength measurement is required, the trade-offs between cost and technological risk must be re-examined. Another question that must be answered is: What "miss and error" rates are acceptable in a detection and tracking sensor? Here again, cost must be a consideration.

A detailed history of vortex sensor development is contained in FAA Report No: FAA-RD-77-23, "Aircraft Wake Vortices: A State-of-the-Art Review of the United States R&D Program", Chapter 6, Vortex Sensors.

2.3.2.2 Vortex Behavior Analysis

Fundamental to the successful development of a wake vortex advisory/avoidance system is a basic knowledge of the vortex phenomena. Understanding of the physics of vortex generation, the vortex roll-up process, vortex structure, vortex transport, and vortex decay was required to facilitate basic systems development. Comprehensive review of the literature of the vortex phenomena is documented in numerous sources. Intensive vortex data collection efforts at Denver Stapleton, Boston Logan, New York John F. Kennedy, London Heathrow, Chicago O'Hare, and Toronto Airports; the National Aviation Facilities Experimental Center (NAFEC); and the NASA Research Centers have contributed to the establishment of the vortex behavior data base.

TSC has primary responsibility for the management of research, data collection, and analysis required to develop the statistical data base which can be used to determine the causative factors and nature of vortex behavior.

An expanded description of the research efforts in vortex behavior analysis can be found in Chapters 3, 7 and 8 of FAA Report No. FAA-RD-77-23. (See full reference in para. 2.3.2.1).

2.3.2.3 Hazard Definition

The third major work effort addressed in the original E&D Program Plan (February 1973) is hazard definition. The objective of hazard definition was to establish the conditions in terms of vortex and aircraft parameters wherein the vortex wake is a hazard to specific classes of aircraft. It is also necessary to define the spatial extent of the hazardous region.

"Hazard definition", as the term is used here, is the method for determining if an aircraft on a given flight path will be sufficiently distrubed by vortices in the vicinity of that flight path to the extent that it could be dangerous to continue the approach. There are four basic steps to the hazard definition process:

(a) Determination of the relevant vortex parameters.
(b) Derivation of an analytic method for calculating the forces and moments on the encountering aircraft.
(c) Derivation of methods for calculating the dynamic response of aircraft in the vortex flow field.
(d) Selection of hazard criteria to judge if a given degree of upset is hazardous.

A threefold approach has been used in addressing the hazard definition task: analytical modeling to calculate vortex-induced forces and aircraft response; computer and manned simulations, towing tank tests, and wind tunnel tests to validate the analytical modeling, and flight test experiments using instrumented aircraft to probe vortex flow fields.

The results from hazard definition experiments have been incorporated in the behavior and tracking algorithms and will be used in the final determination of separation criteria matrices for the Wake Vortex Avoidance System. A further description of the results of hazard definition experiments can be found in Chapter 5, FAA-RD-77-23 (referenced in para. 2.3.2.1) and a comprehensive listing of available literature can be found in Report No. FAA-RD-76-43, "Aircraft Wake Vortices - An Annotated

Bibliography (1923-1975) " J.N. Hallock, January 1976.

2.3.2.4 Related Effort: Aerodynamic Allevation

Experimental research is being conducted by the National Aeronautics and Space Administration (NASA) in the area of wake vortex alleviation through aerodynamic methods. Aerodynamic alleviation is the general term describing modifications made to the airframe or airfoil which will alter the vortex structure to decrease adverse effects of the wake vortex on following aircraft. The immediate goal of aerodynamic vortex minimization is to decrease the required longitudinal spacing between aircraft by modifying the vortex structure in such a way that if a vortex encounter does occur, the resulting upset will not exceed the roll control authority or autopilot control capabilities of the following aircraft.

The majority of wake vortex alleviation work in the United States has been conducted by NASA. A reasonably consistent set of alleviation effectiveness criteria and test procedures have evolved. NASA research has concentrated in three basic areas: analytical studies to establish vortex alleviation effectiveness criterion; ground facility testing procedures involving wind tunnels and water towing basins; and flight test techniques.

Flight tests have played an important role in the coordinated research program to develop wake vortex alleviation techniques. The contribution of flight testing to the program lies in three critical areas: to verify that the more flexible and cost-effective ground-based facilities are suitable for developing alleviation devices and techniques developed in the small scale test environment; and to assess operational feasibility of the various techniques. Three basic flight test techniques have evolved from the wake turbulence research: flow visualization, upset measurements of encountering aircraft, and velocity profile measurements.

Various alleviation techniques have been developed and investigated for operational feasibility; such as deployed splines, mass injection, split flaps, modified spoiler deployment, and various types of wing "fences". To date the spoiler modification has shown the greatest potential for alleviation under operational conditions. This technique has not been fully validated for all types of "heavy" aircraft in low altitude approach conditions where the vortex field enters ground effect. Flight tests are being conducted at NASA's Dryden Flight Research Center to complete this phase of the flight test program.

For a complete discussion on the NASA research experience see NASA report: SP-409 "NASA Symposium on Wake Vortex Minimization" and Chapter 4, "Aerodynamic Minimization", FAA-RD-77-23 (See reference para. 2.3.2.1).

2.3.3 Discarded Technical Approaches

2.3.3.1 Vortex Warning System

Early conceptual planning envisioned the development of a Vortex Warning System as the first generation system to cope with the wake vortex problem. Initial research led developers to pursue a simpler course than a Vortex Warning System which required active vortex detection and tracking sensors in the approach corridors. The concept of a relatively simple warning system with vortex sensors may still be viable for smaller airports. Because capacity gain is the primary objective of wake vortex advisory/avoidance system development, further development of a warning system for the smaller air terminals has been terminated; because analytical studies failed to validate the cost effectiveness of this concept.

2.3.3.2 Dissipation Techniques

The original E&D planning identified ground-based dissipation techniques as a related research effort. NASA through an inter-agency agreement with FAA assumed the responsibility for investigating dissipation techniques.

Three basic techniques were investigated: barriers, blowing devices, and suction devices. Although some variation of these basic techniques might prove feasible, no technique was deemed operationally practical on a large scale. A final report, NASA CR-132365, "Model Experiments to Evaluate Vortex Dissipation Devices Proposed for On or Near Aircraft Runways", August 1973, details the experimental research conducted in this area. All research activity on dissipation concepts has been terminated.

2.3.4 Data Collection Sites

To adequately document vortex behavior in the operational environment and to investigate the transport, strength, and decay of aircraft wake vortices; four test sites (Denver Stapleton, New York John F. Kennedy, London Heathrow, and Chicago O'Hare) were instrumented to track vortices shed by landing aircraft and one site (Toronto International) for departing aircraft.

The approach zone in the middle marker region was monitored as this is potentially the most hazardous vortex region since all aircraft must pass through the same airspace to execute a landing. The takeoff zone is being monitored to determine if departure procedures applicable to aircraft departing behind heavy aircraft are unduly restrictive because of wake turbulence considerations.

The test program effort has emphasized acquisition of statistical data required in the development of a vortex behavior model. The approach followed at the test sites generally consisted of:

(a) Deployment of vortex sensors and their use in tracking vortex motion and decay as a function of time.

(b) Deployment of a meteorological sensor network.

(c) Reduction of the acquired data to evaluate the performance of vortex sensors; verification and refinement of the predictive model of vortex motion and decay; and the establishment of an adequate data base for the design of vortex advisory/avoidance systems.

A detailed description of the individual test sites can be found in FAA Report FAA-RD-77-23, (See reference para. 2.3.2.1), Chapters 7 and 8. A complete analysis of the Heathrow project activities and data is available in the joint U.S./U.K. final report, FAA-RD-76-58 Vols. I & II, "Joint U.S./U.K. Vortex Tracking Program at Heathrow International Airport", March 1976.

2.3.4.1 Denver Stapleton

The Stapleton test site was established in August 1973 in the approach corridor to Runway 26L. Between August and November 1973 the vortex tracks from 7000 aircraft landings were recorded. The primary objective of the Stapleton project was to acquire vortex behavior data at an airport located at a high mean sea level altitude and to further confirm the adequacy of the traffic separation standards then in use.

Figure 2-3 is a configuration diagram of the Stapleton test site.

2.3.4.2 New York John F. Kennedy Test Site

The JFK Vortex Test Site was established as a primary development site for vortex sensor systems. Sensor systems tested at JFK included: Doppler acoustic systems, pulsed acoustic systems, laser Doppler systems and anemometer systems. Final reports have been published on these sensor development efforts. The site was also utilized as a primary test site to determine the correlation between vortex behavior and meteorological conditions. During the operation of the JFK site over 14,000 vortex data tracks were acquired. The JFK site was deactivated in January 1977.

Figure 2-4 is a configuration diagram of the JFK Test Site.

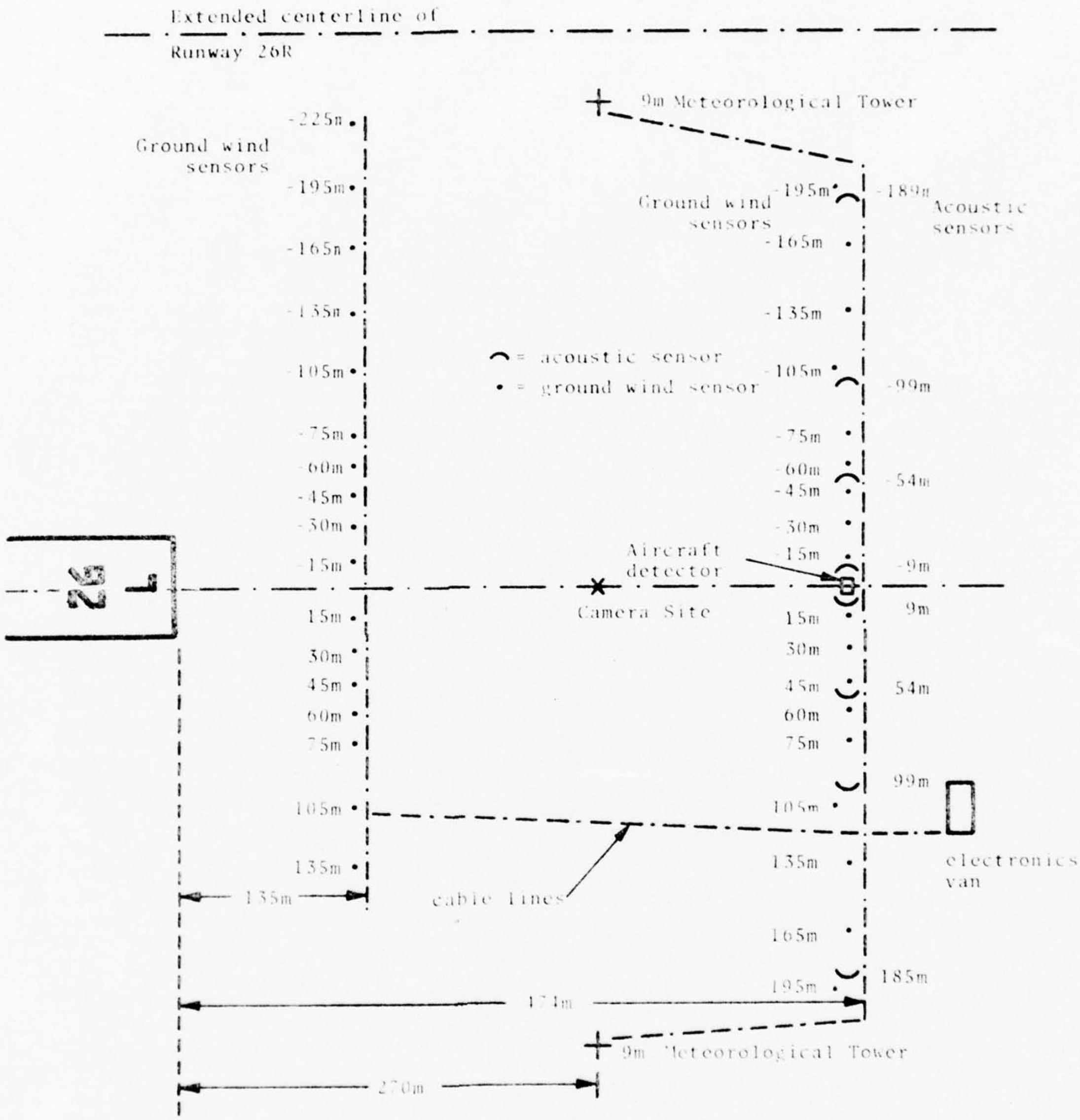

Figure 2-3. Overall Plan View of Sensor Locations at Stapleton Airport.

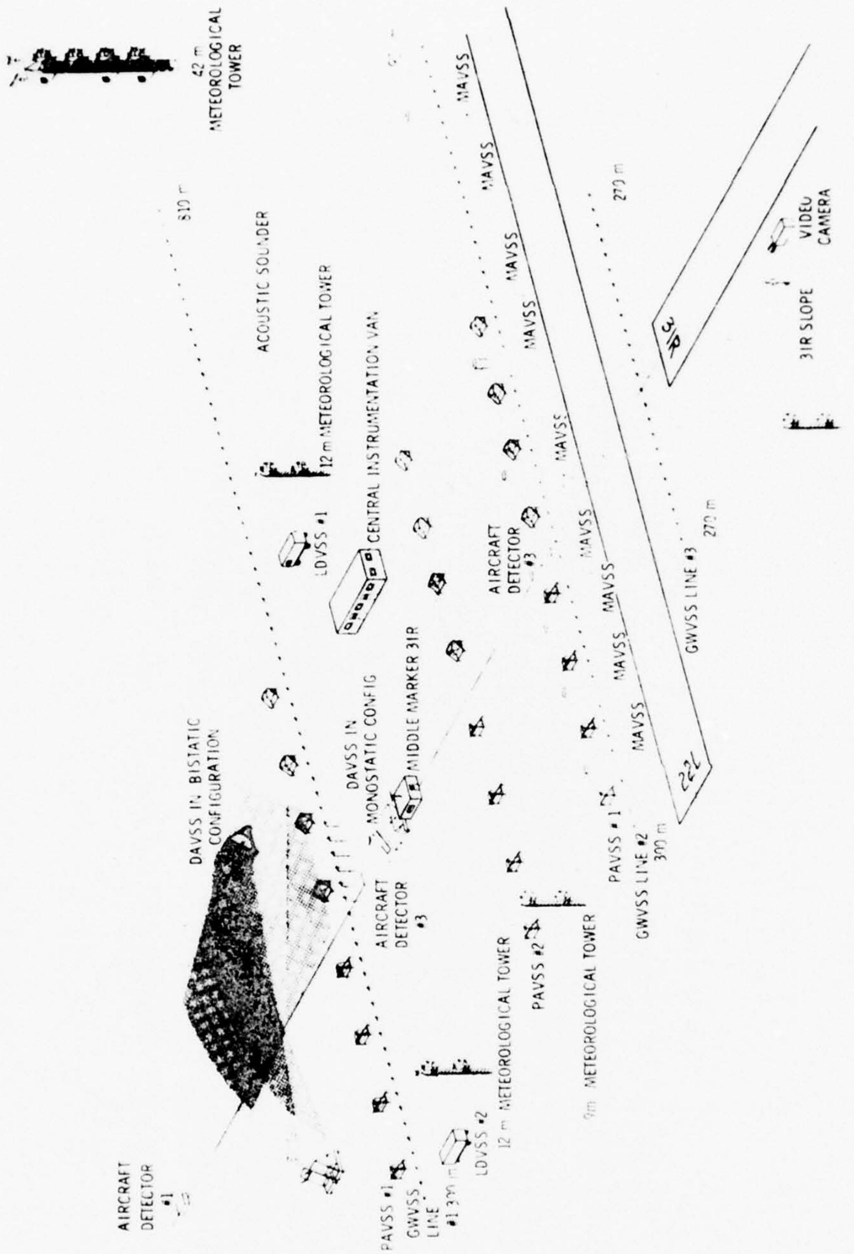

Figure 2-4. JFK Test Site.

2.3.4.3 London Heathrow Vortex Tracking Program

In May 1974 a joint U.S./U.K. Vortex Tracking site was established on Runway 28R at the London Heathrow International Airport. The primary objective of this joint project was to correlate pilot reports of vortex incidents with a vortex tracking system and further acquire vortex behavior data in an operational environment. Approximately 12,500 vortex data tracks were acquired at Heathrow activity and data analysis has been published: FAA-RD-76-58, I & II, joint US/UK Vortex Tracking Program at Heathrow International Airport, March 1976.

Figure 2-5 shows the test site configuration at Heathrow.

2.3.4.4 Toronto Vortex Test Site

The major data collection efforts in the vortex program has centered on the approach and landing region. Vortex data on departing aircraft are extremely limited. A joint US/Canadian effort was initiated to acquire a statistically valid and meteorologically correlated data base on the vortex behavior associated with aircraft on takeoff. A test site was established at Toronto International Airport on Runway 23L in April 1976. This data collection activity continued through October 1977, a coordinated US/Canadian report will be published in early 1978.

Figure 2-6 is a configuration diagram of the Toronto test site.

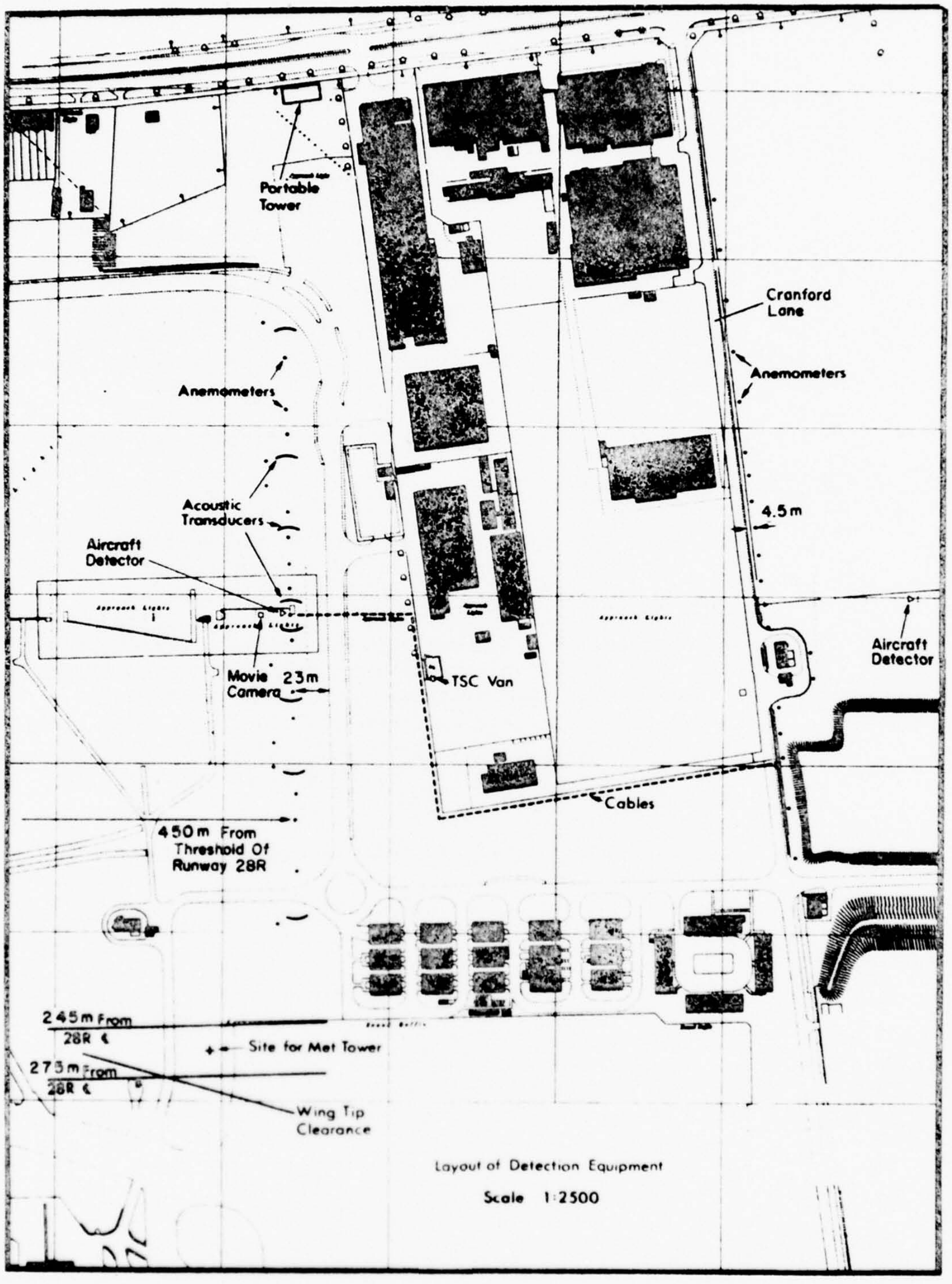

Figure 2-5. The Site Layout of the Equipment on the Approach to Runway 28R at Heathrow.

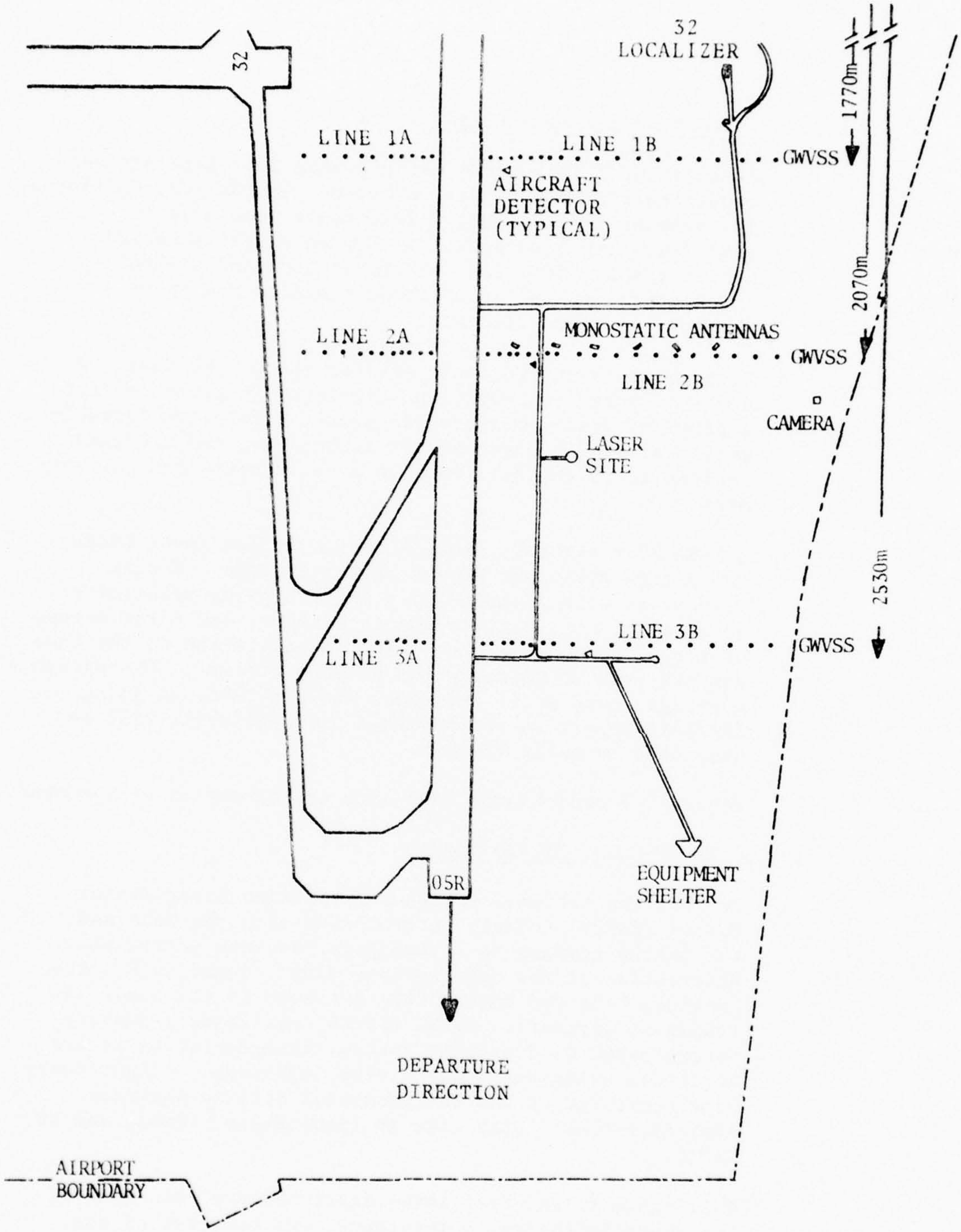

Figure 2-6. Overall Plan View of Toronto Vortex Test Site.

2.3.4.5 Rosamond Dry Lake Flight Tests

A series of flight tests using a NASA B747 aircraft were conducted at Rosamond Dry Lake near Edwards AFB, California in December 1975. These flight tests were a joint NASA/FAA project supported by Dryden Flight Research Center (NASA), TSC, FAA Western Region, and several contractors, including Lockheed Missiles and Space Company, and Aero-Vironment.

Four major objectives were set for the flight test: A study of vortex alleviation techniques in ground effect, a study of vortex bursting in ground effect, an investigation of ground-based sensor techniques, and a characterization of the B747 wake in a semi-controlled environment.

A NASA B747 aircraft flew 54 passes at low-level (Under 250 meters AGL) over ground sensor systems. Vortex velocities were measured by a laser Doppler velocimeter, an array of monostatic acoustic sensors, and three arrays of propeller anemometers. Flow visualization of the wake was achieved using smoke and balloon tracers. Photographic coverage, both still and cine, was provided. A joint FAA/NASA Report on the Rosamond Dry Lake tests will be published in early FY-1978.

Figure 2-7 depicts the test site configuration at Rosamond.

2.3.4.6 NAFEC Tower Fly-By Tests

In 1970 the National Aviation Facilities Experimental Center (NAFEC) jointly participated with the NASA and the Boeing Company to investigate the wake vortex characteristics of the then newly-arrived "jumbo jets", the Lockheed C-5A and Boeing 747, and some of the older jet transport aircraft. NAFEC flight test teams primarily concentrated on measuring vortex characteristics at low altitudes using the tower fly-by technique. Flight tests were conducted at the Environmental Science Services Administration (ESSA) site at Idaho Falls, Idaho, and at NAFEC.

Full scale flight test investigations have been made of the characteristics, persistence, and movement of the trailing vortices generated by both reciprocating and jet aircraft. During the years 1970-1973 flight test

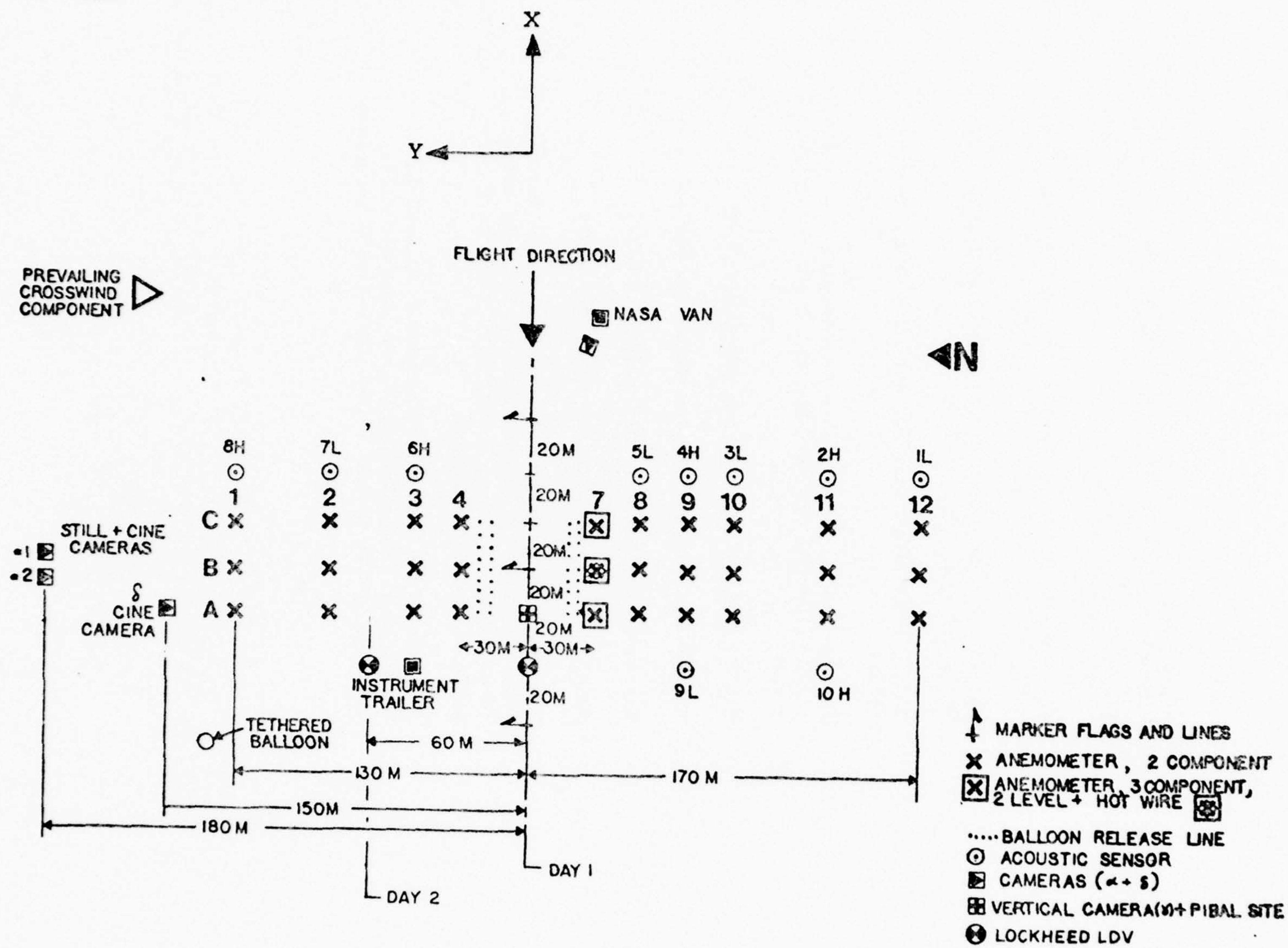

Figure 2-7. Test Array Layout, Rosamond Dry Lake, Dryden FRS (NASA).

investigations, using the tower fly-by and flow visualization technique, have been performed with the following aircraft: DC-10, DC-9, DC-7, B747, B727, B707, C-5A, C-141, L1011, and CV-880.

Further details of flight test investigations and data analyses can be found in the following reports:

FAA-FS-71-1, Feb. 71, Vortex Wake Turbulence - Flight Tests Conducted During 1970.

DOT-TSC-FAA-72-2, Jan. 72, Vortex Sensing Tests at NAFEC.

FAA-RD-73-141, Nov. 73, The Measurement of the DC-7 Trailing Vortex System Using the Tower Fly-By Technique.

FAA-RD-74-173, Nov. 74, (As above for DC-9).

FAA-RD-73-156, June 74, (As above for B747).

FAA-RD-74-90, Aug. 74, (As above for B727).

FAA-RD-75-15, Mar. 75, (As above for B707).

FAA-RD-75-127, May 75, Measurement of the Trailing Vortex Systems of Large Transport Aircraft Using Tower Fly-By and Flow Visualization (Summary, Comparison, and Application).

FAA-AFS-1-76-2, May 76, Abbreviated Full-Scale Flight Test Investigation of the Lockheed L1011 Trailing Vortex System Using Tower Fly-By Technique.

3.0 PROGRAM

3.1 Wake Vortex Avoidance Concept

The concept of wake vortex avoidance is based on three considerations which the available wake turbulence data supports. These are:

(a) Meteorological conditions exist a large percentage of time which cause vortices to move quickly off the flight path or decay rapidly in the approach corridor such as to not present a hazard to aircraft following on the same flight path.

(b) The duration, intensity and movement of vortices can be reliably predicted if adequate knowledge of existing meteorological conditions and the generating aircraft's characteristics are known.

(c) Vortices can be detected and tracked at selected points along the approach or departure paths through the use of existing sensing techniques.

From the first consideration, it is evident that we are penalizing capacity through the use of large, fixed spacings when most of the time no hazard exists. Looking at it another way, through the Wake Vortex Avoidance program it will become possible to tailor spacings to the actual hazard and, thereby, achieve an increase in runway capacity.

The second consideration allows vortex decay and motion to be predicted with sufficient accuracy so spacings can be adjusted for the sequence and types of aircraft arriving or departing a terminal. Until recently the lack of knowledge about the life-cycle of wake vortices generated by today's large aircraft mandated large separation distances for following aircraft and thus limited runway capacities. Analysis of the extensive data on vortex behavior as a function of meteorological conditions has indicated that there are wind conditions which predictably remove vortices. A wind rose criterion has been developed and tested to determine when the separations could be uniformly reduced to 3 nautical miles for all aircraft types rather than the 3, 4, 5, and 6 mile separations currently required.

3.2 Vortex Advisory System (VAS)

A Vortex Advisory System (VAS) was designed to take advantage of the wind rose criterion. The system is based on comparing the measured wind magnitude and direction (with respect to each runway heading) with the wind criterion. The comparison indicates via a simple display, when separations could be safely reduced to 3 nautical miles for all traffic.

Chicago's O'Hare International Airport was selected for the system feasibility tests based on the following criteria: adequate available real estate for the VAS equipment, operations near or beyond saturation during VFR and/or IFR conditions and a significant percentage of jumbo jet operations in the traffic mix. The current effort at Chicago O'Hare relative to the VAS involves the evaluation of the system capability to provide the criteria for reducing longitudinal separations when either the wake vortices have been blown out of the approach corridor or when the vortices have decayed and no longer present a potential hazard to the following aircraft.

The VAS feasibility testing was implemented using an instrumentation system to measure the vortex positions as a function of time and the ambient meteorological conditions and correlating these with the VAS displayed separation criteria. The amount of time that the VAS indicates reduced separations can be used is being evaluated to determine how many additional operations could be accommodated if reduced separations were in effect and how much in delay dollars could be saved. This evaluation will be performed under all the usable combinations of approach and landing runway scenarios as well as under both VFR and IFR weather conditions. Adequate data have been collected to allow a statistically valid evaluation of the system's ability to determine when the separations may be reduced to 3 nautical miles for all aircraft types and to determine that the criterion algorithm contains adequate safety margins for all meteorological and vortex conditions.

3.2.1 VAS Design

The VAS installed at O'Hare was designed and implemented as a concept feasibility and performance demonstration system. This design intentionally did not include reliability or maintenance considerations as this demonstration system was to be completely removed from O'Hare upon completion of the evaluation. A detailed system design specification has been completed for the demonstration system and will be used as the foundation for the Technical Data Package which is required for procurement of the system for NAS implementation.

As a result of the first six months of performance testing it was decided to convert the demonstration system at Chicago O'Hare into an operational system which will remain at O'Hare as part of that airport's operational equipment. Therefore, design changes will be implemented into the system to incorporate high reliability equipment and to provide for system maintainability. Upon completion of the design changes, the system specification will be revised to reflect the latest system configurations.

After implementation of the VAS operational system at O'Hare, an operational evaluation test will be performed for six months during which the system will be utilized by controllers for establishing interarrival separations at O'Hare according to the VAS criteria. The VAS performance evaluation instrumentation will be kept in place to assure proper evaluation under operational conditions.

3.2.1.1 Meteorological Towers

The VAS consists of a network of seven instrumented meteorological towers whose signals are transmitted to a centrally located processor which uses a simple algorithm to determine the vortex conditions in the approach corridor and displays the appropriate interarrival separation to the air traffic controllers in both the tower cab and the common IFR room. As shown in Figure 3-1, the tower network for O'Hare consists of seven 50-foot meteorological towers positioned to measure the wind close to each approach corridor. A network of towers is required as tests have proved the inhomogenity of the atmosphere precludes the use of a single centrally located sensor for the measurement of wind. The towers are free standing on a reinforced concrete base and are marked and lighted per FAA Advisory Circular 70/7460-1.

3.2.1.2 Meteorological Sensors

Each tower is instrumented with three wind magnitude and direction sensors, one at the 50-foot level and the other two at the 47-foot level. The 47-foot sensors are mounted on opposite sides of the tower to provide a measurement undisturbed by tower shadowing. The wind speed sensor has the following salient characteristics: range of 0-100 kts, accuracy of $\pm$ 0.5 kts or 2%, threshold of 0.75 kts maximum, and a distance constant of 30 feet, and a damping ratio of 0.4-0.6. All sensor and communication electronics at

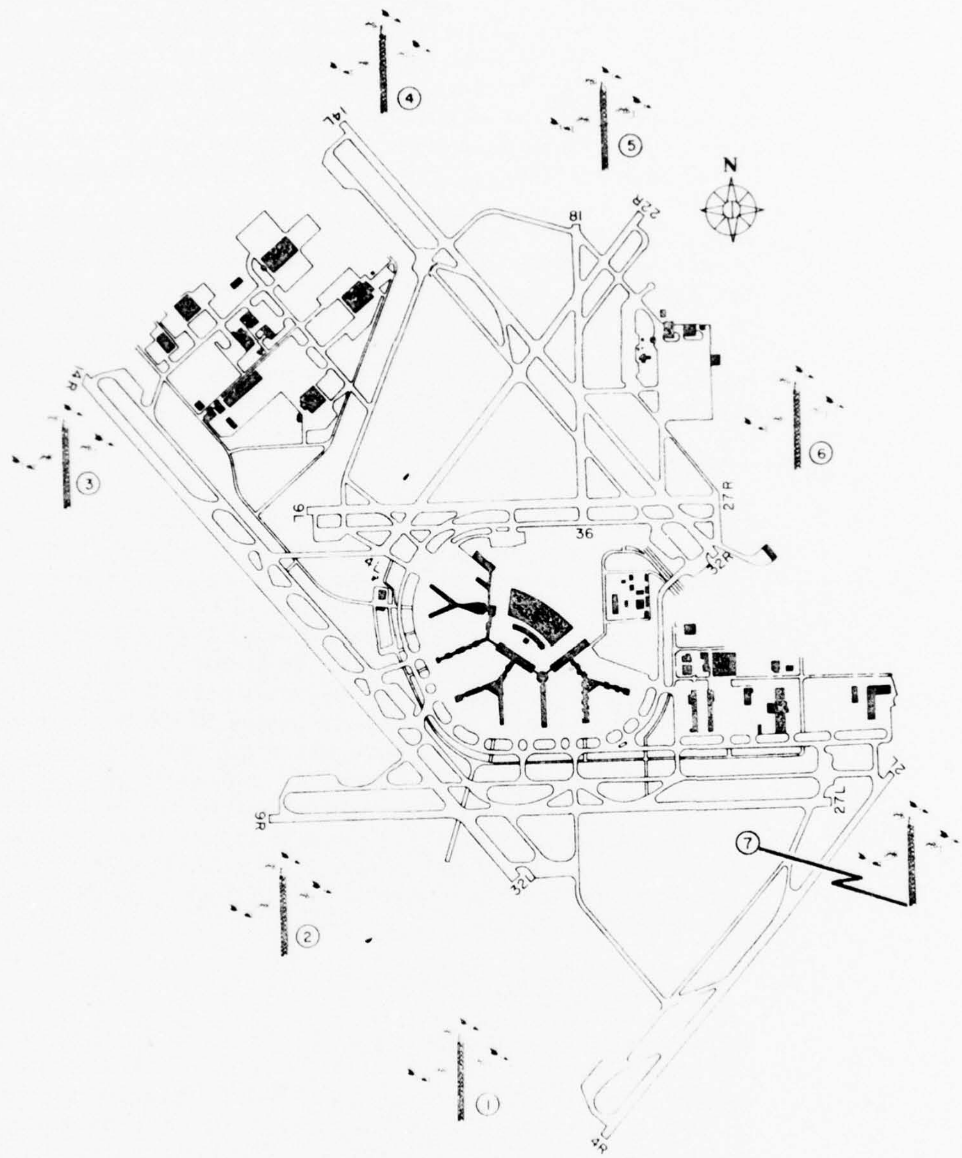

Figure 3-1. VAS Meterological Tower Network (ORD).

each tower are housed in an environmental enclosure. Each tower is supplied with a 220-110 volt 60 Hz power source, a 2 KVA line voltage regulator, and a transient arrestor for lightning protection.

3.2.1.3 Tower Data Transmission Subsystem

Transmission of the data from the set of widely dispersed towers to the centrally located processor is accomplished with standard hardware. As shown in Figure 3-2, the VAS block diagram, a multiplexer successively samples the sensor outputs and converts them to a parallel digital word which is serialized and transmitted over existing FAA telephone lines to a central facility where receivers reconvert the data to a parallel format for input to a microprocessor. A Datel System DAS-16, 16-channel 12-bit data acquisition system sequentially scans the sensor outputs and converts them to a 16-bit word consisting of a 4-bit address and 12 bits of data. The DAS-16 operates under the control of a Larse Corp. LLS-111 sending unit which commands the channel scan, converts the output data to serial format, and transmits the data to a Larse Corp. LCR-211 receiving unit where the data is reconverted to a parallel format. The sampling rate is fixed by the LSC-111 at 5600 bits/sec resulting in a word rate of 5600/16 or 350 words/sec.

3.2.1.4 Meteorological Data Processing

Individual microprocessors (Intel SBC 80/20) are used to reprocess the data from each meteorological tower. The microprocessors contain 8K of Read-Only-Memory and 2K of Random-Access-Memory. Each microprocessor is packaged on a single plug-in board.

The microprocessors sample the meteorological data output from each LCR-211 receiver at a rate of 2 samples/sec. The sampled wind magnitude (R) and wind direction (θ) are used to compute a one-minute running average ($\overline{R}$ and $\overline{\theta}$) by the following scheme: for each sample compute $U=R\sin\theta$ and $V=R\cos\theta$, compute $\overline{U}$ and $\overline{V}$ using a running 128-sample average, and compute $\overline{R}=(\overline{U}^2+\overline{V}^2)^{1/2}$ and $\overline{\theta} = \mathrm{Tan}^{-1}\,\overline{V}/\overline{U}$.

A wind gust is defined using a 30-second window. The sampled R is averaged using an 16-sample running average.

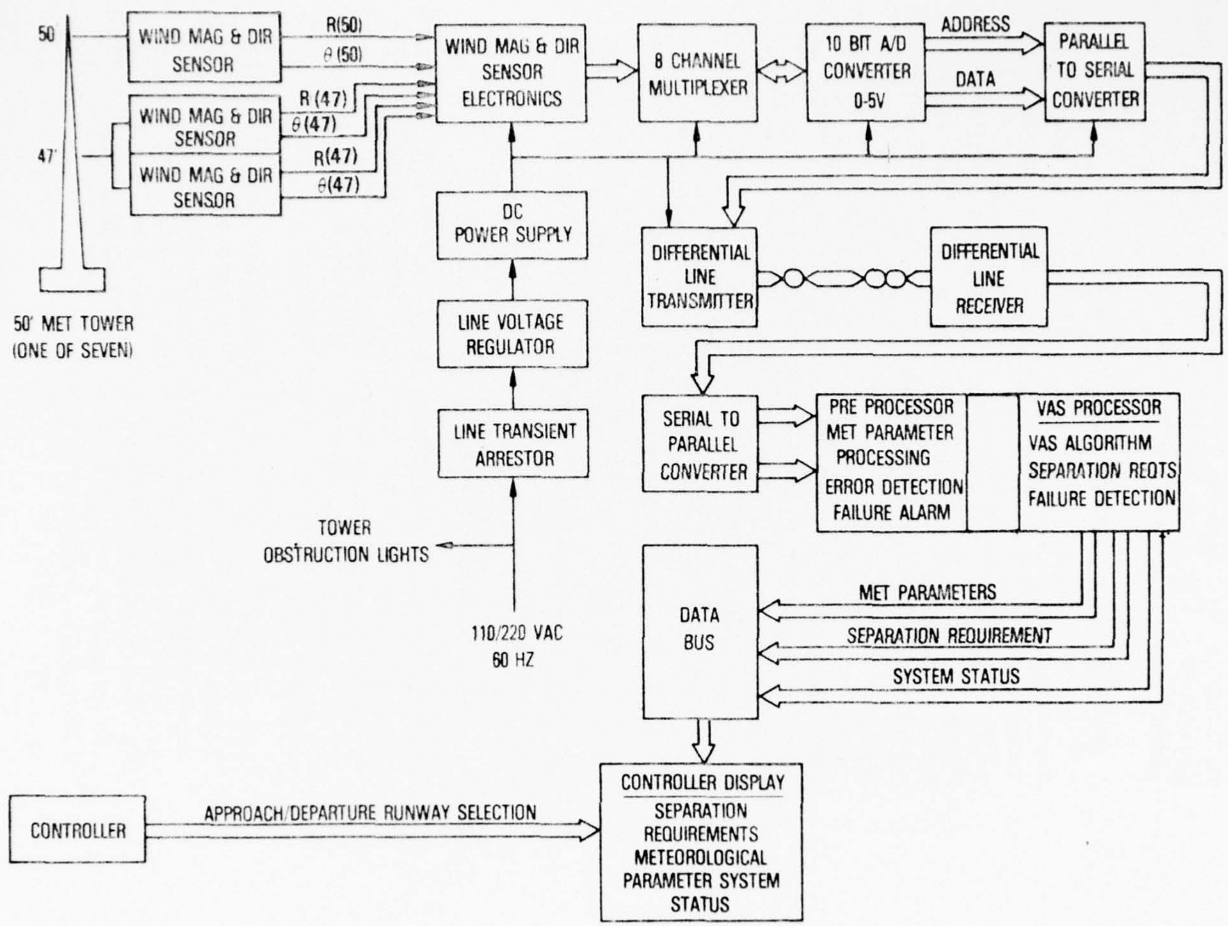

Figure 3-2. Vortex Advisory System: Functional Block Diagram.

(Transient spikes in the data are eliminated by a comparative process). Any measured peak must be at least 9 knots above $\overline{R}$ to be considered a gust. A measured gust is displayed to the controller for 30 seconds, unless a larger gust is observed, in which case the new value is displayed.

The R and θ from the three sensors on each tower are compared after each sampling interval. A sensor-failure bit is generated if the R of any sensor differs by more than 3 knots or if the θ of any sensor differs by more than 10°. Normally, the 50-foot sensor output is used for the VAS algorithm. If the 50-foot sensor output fails, the microprocessor switches to a 47-foot sensor and selects the sensor which is not in the shadow of the tower. Upon detection of a failure, a failure word is generated identifying the sensor which failed, or if two sensors disagree, which tower has been shutdown.

3.2.1.5 Separation Requirement Determination

The individual tower microprocessors are also used to calculate the allowable aircraft landing separations for a runway based on the wind speed and direction measured by the instrumented tower. As shown in Figure 3-3, an elliptical VAS algorithm is used which includes a buffer or "transition zone." The major and minor axes of the inner ellipse are 13.0 and 6.0 knots, respectively, and 14.0 and 7.0 for the outer ellipse. The 1 knot transition zone allows for a gradual change between the separation states, as opposed to an abrupt change, giving the air traffic controller working a line of approaching aircraft the capability to continue to land an aircraft at the middle marker when the separation conditions change.

Separation requirements are displayed to the controller via Red and Green lights; Red indicates a 3-4-5-6 nautical mile separation requirement, Green allowing reduction to three nautical miles. The criterion for separation and for changing separations, from one state to another are:

(a) If the wind vector $(\overline{R},\overline{\theta})$ is inside the inner ellipse, the condition is RED, and the 3-4-5-6 separations apply.

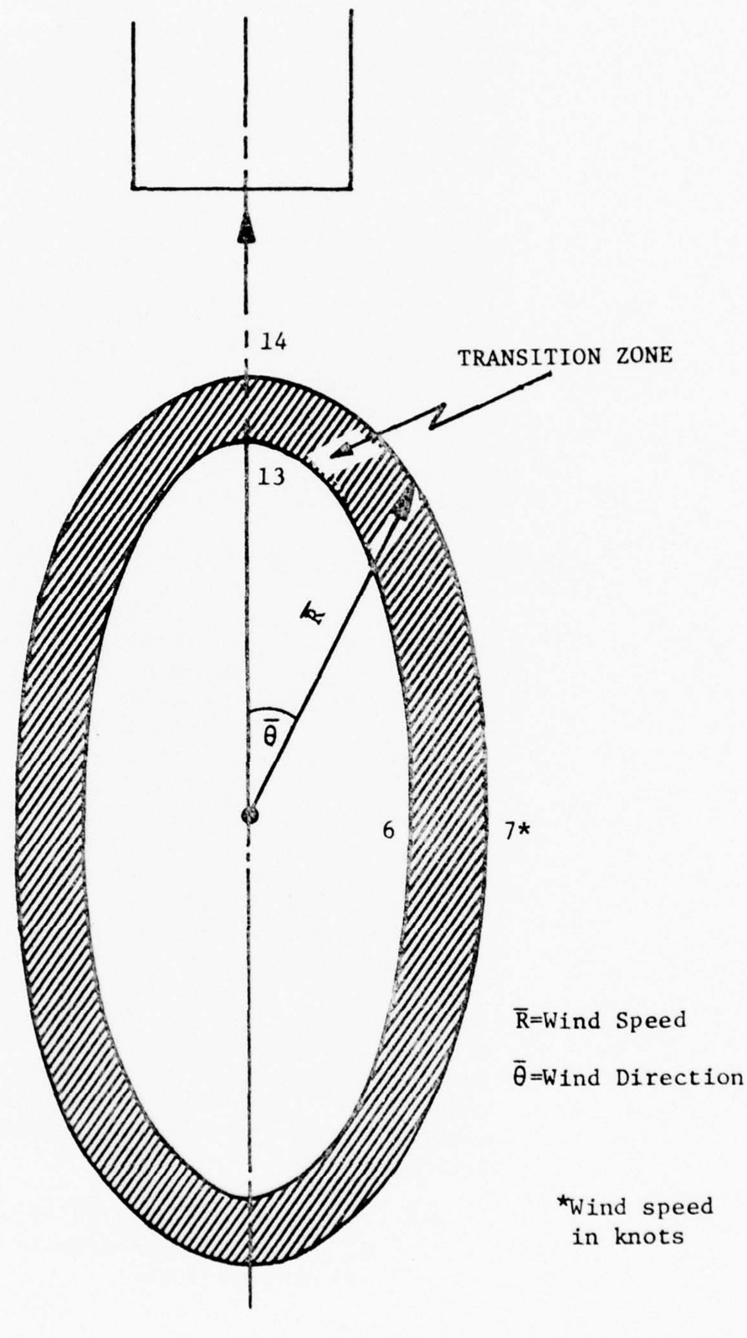

Figure 3-3. VAS Algorithm: Wind Criterion.

(b) If the wind vector $(\bar{R},\bar{\theta})$ is outside the outer ellipse, the GREEN condition exists, wherein all aircraft can be separated by 3 miles regardless of the type of aircraft leading or following.

(c) If the condition is RED and the wind is increasing, the requirement exists for the wind vector to be outside the outer ellipse for 64 seconds before the GREEN light comes on.

(d) If the condition is GREEN and the wind starts decreasing and enters the transition or buffer zone, the GREEN light remains on and the data processor continues the normal averaging routine. If, however, the wind vector actually enters the inner ellipse region, a change to the RED condition takes place immediately. The inner ellipse includes a safety factor in order to allow aircraft a short final to complete the landing safely. Subsequent landings would then be at standard 3-4-5-6 nautical mile separations.

The microprocessors output labelled data onto a data bus for display with the following information for each operating region: $\bar{R}$ to 1 knot, $\bar{\theta}$ to 10°, gust (if applicable) to 1 knot, the vortex condition RED and GREEN for each landing runway, and failure indications.

3.2.1.6 Data Display Subsystem

Two types of displays are used in the VAS, a System Monitor Display (Figure 3-4a) and a Runway Monitor Display (Figure 3-4b).

The System Monitor Display is intended for use by the tower and IFR room supervisors. The display indicates in summary form all meteorological tower outputs and the approach/departure corridors for which the wind measurements apply. Its primary function is to provide an overview of the wind and vortex conditions across the entire airport enabling the supervisor to select an operating configuration which will maximize traffic flow based on the ambient wind conditions and the respective vortex conditions in each approach corridor.

The Runway Monitor Display is designed for use by a controller responsible for traffic control on a single runway. As shown in Figure 3-4b, the controller selects a specific runway via a set of thumbwheel switches. The controller

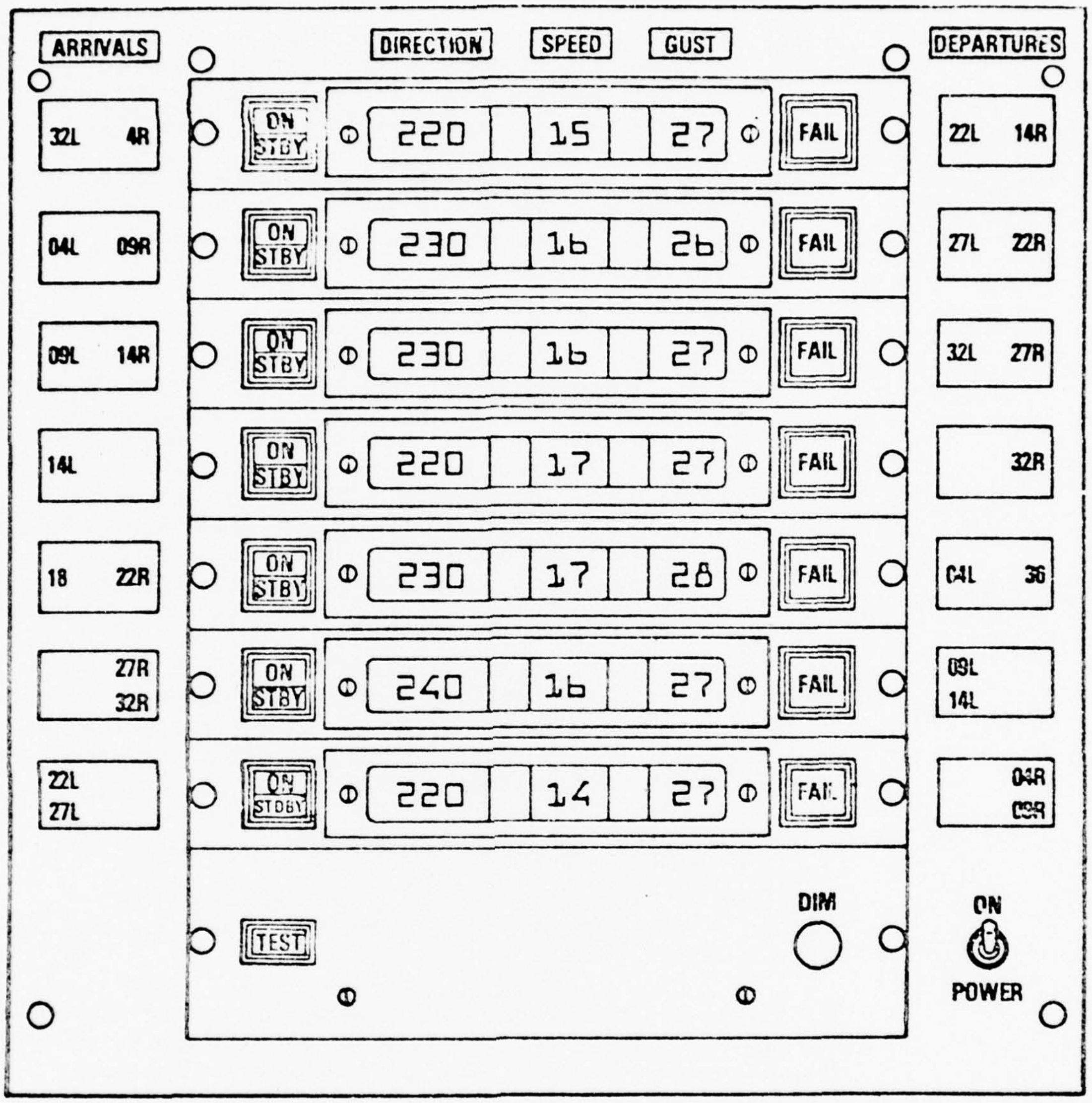

Figure 3-4a. The VAS System Monitor Display.

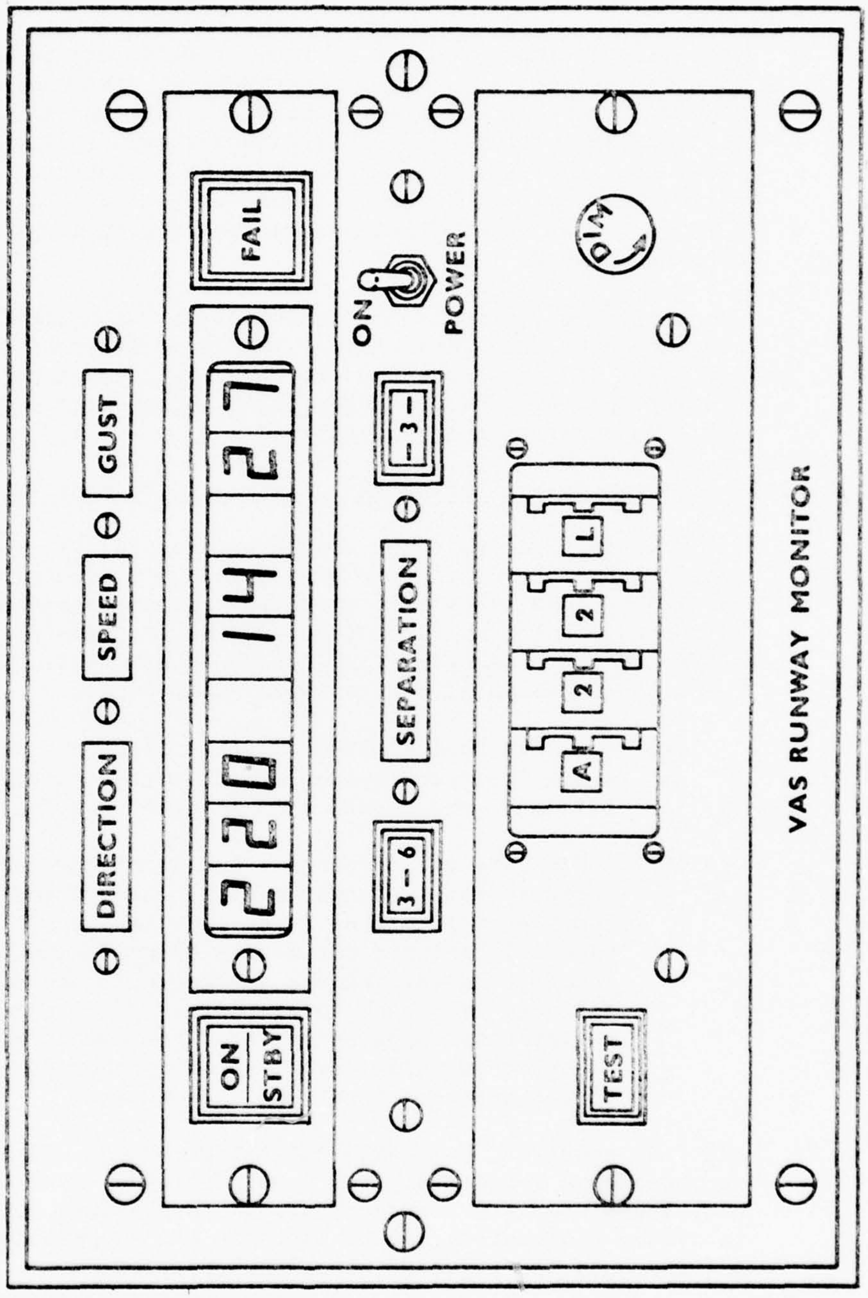

Figure 3-4b. The VAS Runway Monitor Display.

must also indicate whether arrival or departure information is desired: e.g., he enters A32L for arrivals to runway 32-Left and D32L for departures from runway 32-Left. The display thereafter accepts data with the corresponding label from the data bus. Thus, if A32L is entered, wind parameters measured by tower #1 are displayed, while a D32L entry causes wind parameters measured by tower #3 to be displayed.

Separation requirements are indicated by "RED-GREEN' and are indicated only when arrival runway is selected. A RED light indicates the need to maintain 3/4/5/6 nm landing spacing, while a GREEN Light indicates that an all 3 nm separation may be applied.

3.2.1.7 Performance Monitoring and Data Recording Subsystem.

In order to facilitate the maintenance of the VAS equipment console containing the microprocessors, modem receivers, power supplies, etc. also contains system maintenance units which indicate to the maintenance personnel the systems status and repair requirements. The maintenance subsystem has two major components:

(a) A System Monitor Display, described previously, which indicates system status to the maintenance personnel and alerts them in case of a failure.

(b) A separate microprocessor which monitors the outputs from the tower microprocessors and compiles a record of individual failures. The record is printed out hourly or on demand. The printout, detailing the source and types of failures from each tower, serves as an early alert to maintenance personnel that components with higher than normal drop-out rates should be replaced before a total failure occurs.

All data acquired, processed and output by the VAS are recorded on a 9-track digital tape recorder. Each tape contains a complete record of all VAS operations for use in system diagnostics and to meet the FAA's operational requirements for a record of all ATC operations.

3.2.2 Supporting Research Activities

It is inherent in the development of any new operational system that the safety aspects be of prime consideration in the operational use of the system. Additionally, in the case of the Vortex Advisory System, a second basic consideration is that the VAS not impose an unmanageable workload on the controller. These two factors required special attention by the research teams.

Two questions had to be answered before operational implementation of the VAS:

(1) What is the region of operational applicability for VAS operations?

(2) What are the procedural implications and impact on controller workload involved in VAS operations?

The following sections discuss the program projects which were established to seek answers to these questions.

3.2.2.1 Vortex Advisory System Safety Analysis and Associated Data Collection

In establishing the area in the final approach corridors where VAS separations could be applied a comprehensive analysis was necessary to assess whether vortex behavior in the middle marker to threshold region (where the wind measurements for determining vortex status are taken) could be applied in the outer marker to middle marker region. It has been proven that the wider the area of coverage in which VAS separations could be applied the more effective the system will be in increasing runway capacity. Therefore, a thorough analysis of the factors effecting vortex behavior and the associated encounter probabilities was initiated at the Transportation Systems Center. The results of this analysis will be published as a formal FAA report.

To support the analytical assessment, a test program utilizing a laser Doppler velocimeter (LDV) to track vortices in free air between the middle and outer markers was established at O'Hare International Airport. The LDV test site was located in the approach corridor of runway 27R and vortex tracking data between the 700 and 800 foot levels is being collected, reduced, and analyzed. This analysis of vortex tracking data will be published as Volume II of the VAS Safety Analysis report.

3.2.2.2 Vortex Advisory System Simulation: Digital Simulation Facility (NAFEC)

This simulation project was conducted to determine the procedural implications of the Vortex Advisory System (VAS) on the Air Traffic Control (ATC) System within the Chicago O'Hare International Airport terminal environment. The objective of the simulation was to demonstrate possible capacity gains of VAS operations at O'Hare and assess the impact of VAS on controller workload.

Utilizing the NAFEC Digital Simulation Facility (DSF), a real-time simulation of the Chicago O'Hare airside operations was conducted from March through June 1977. There were a 105 data runs of one hour and twenty minutes duration completed during the test period.

The system was saturated with a traffic mix consisting of 20 percent heavy aircraft, 70 percent large aircraft, and 10 percent small aircraft. This traffic mix was representative of a 5-day sampling of Chicago O'Hare operations in January 1977, with a total traffic density of 150 aircraft per hour (90 arrivals, 60 departures).

Two runway configurations were exercised in the VAS Green, Red, and Transition modes. That is, during VAS Green operations a fixed 3 mile reduced separation between all aircraft types, during VAS Red operations 3, 4, 5, and 6 mile standard separations, and transition between the two modes. In the transition modes two conditions were exercised: middle marker to touchdown, outer marker to touchdown, and 20-mile fix to touchdown.

Preliminary analysis identified the following trends:

(a) No procedural implications emerged which would deter the implementation of VAS at O'Hare.

(b) Capacity increase can be obtained in sufficient percentile to support prior cost/benefit analyses.

(c) A single separation standard appeared procedurally desireable for the entire terminal area.

(d) Trends became more pronounced as the separation reduction zone increased in size.

(e) The Vortex Advisory System could be a factor in establishing runway usage configurations.

(f) An orderly transition of separation modes can be accomplished in five minutes.

A comprehensive and further detailed analysis of the DSF project will be published as a formal FAA report in FY-1978.

3.2.3 Operational Demonstration, Test and Evaluation

A six month operational demonstration and evaluation of the VAS will be conducted at O'Hare International Airport terminating in May 1978. This demonstration and test will measure: (1) The effectiveness of VAS capability to provide reduced interarrival separations for all aircraft pairs (when meteorological conditions permit); (2) The impact of VAS operations on terminal area traffic management; (3) The adequacy of maintenance and reliability considerations; (4) user acceptance of VAS procedures. The operational test and evaluation will be conducted by the O'Hare ATCT with the support of Regional Airways Facilities divisions and NAFEC.

These tests will provide the foundation for changes in the air traffic control procedures that may be required to effectively integrate the VAS into the National Airspace System. This test and evaluation should also provide the operational and technical justification for decisions on the integration of Vortex Advisory Systems into other major U.S. air terminals.

In order to effectively measure the operational suitability several factors must be evaluated:

(a) Suitability and practicality of the information provided by the VAS to approach control personnel in an actual air traffic control environment including human factors considerations.

(b) Potential increase in air traffic operations for all possible runway and approach scenarios using representative meteorological and traffic flow conditions.

(c) Workload imposed on the ATC system by the use of the VAS to determine separations and the effect of change in the separation standards based on the VAS criteria.

(d) Maintenance support required for calibration, operation and periodic maintenance of the VAS equipment.

(e) Suitability of the VAS to the airport environment.

This operational testing will provide the key answers as to the potential effectiveness and compatibility of the VAS in the National Airspace System.

3.3 Wake Vortex Avoidance System (WVAS)

The VAS was designed to meet the current capacity needs of the major high density air terminals and the forecast capacity increase into the early 1980's. In order to meet the demand forecast for the late 1980's and the early 1990's, the FAA is developing advanced systems which will meld together in the future traffic management system. These subsystems collectively allow a significant increase in the NAS capacity without increasing the number of airports or significantly enlarging the existing major terminals. This planned increase in capacity requires the reduction of the longitudinal spacings between arriving and departing aircraft in the major terminal areas.

The VAS itself is not capable of allowing separations below three miles as the VAS is entirely predictive in nature. Also, the VAS requires large safety margins to allow for those cases when vortices might still be a problem at slightly less than three miles.

A system must therefore be designed which could allow reduced separations down to at least 2 miles. Since separations can be set by the approach controller some 15-30 minutes in advance of a landing, prediction of vortex motion is a necessity. During the final approach using separations set by the prediction, sensors will track the vortex in the terminal area to assure that the approach corridor is clear relative to the approaching aircraft.

3.3.1 WVAS Design

The vortex research completed to date has verified that the motion and life cycle of vortices can be forecast when certain parameters such as aircraft type and meteorological conditions in the terminal approach zone are known. These data could be used in a dynamic predictive model which would allow the prediction of vortex behavior for a known sequence of aircraft approaching a terminal area. The prediction might be extended to some 15-30 minutes prior to the aircraft touchdown.

Vortex sensor development and evaluation studies already completed have verified that vortices can be detected and tracked in real-time in the terminal area at relatively low altitudes (250 ft. or less).

Current efforts in the measurement and determination of vortex strength as a function of time have verified that this important parameter could be measured by sensors such as the laser-Doppler velocimeter or the monostatic acoustic sensors.

The basic elements of a system that would proivide positive vortex avoidance in the terminal area while allowing tailored vortex spacings to two miles or less have already been substantially developed. The elements must now be combined into a total system, automated to interface with both the ARTS III and Metering and Spacing systems, and the total Wake Vortex Avoidance System demonstrated at an operational airport. Figure 3-5 is a block diagram of the total automated Wake Vortex Avoidance System which will be designed upon completion of the evaluation of the VAS.

In the WVAS, the predictive model receives aircraft type and sequence data from the ARTS computer and meteorological data from the VAS processor whenever the approach controller or metering and spacing system requests terminal approach spacing for a specific aircraft. The predictive model, based on these inputs, determines the minimum spacing for the following aircraft and provides that output to the Metering and Spacing System computer or to the controller display. The separation criteria provided is purely predictive at this point.

As the aircraft nears the final approach path, the vortex sensors detect and track the vortices from the aircraft preceding the aircraft of concern. Vortex strength

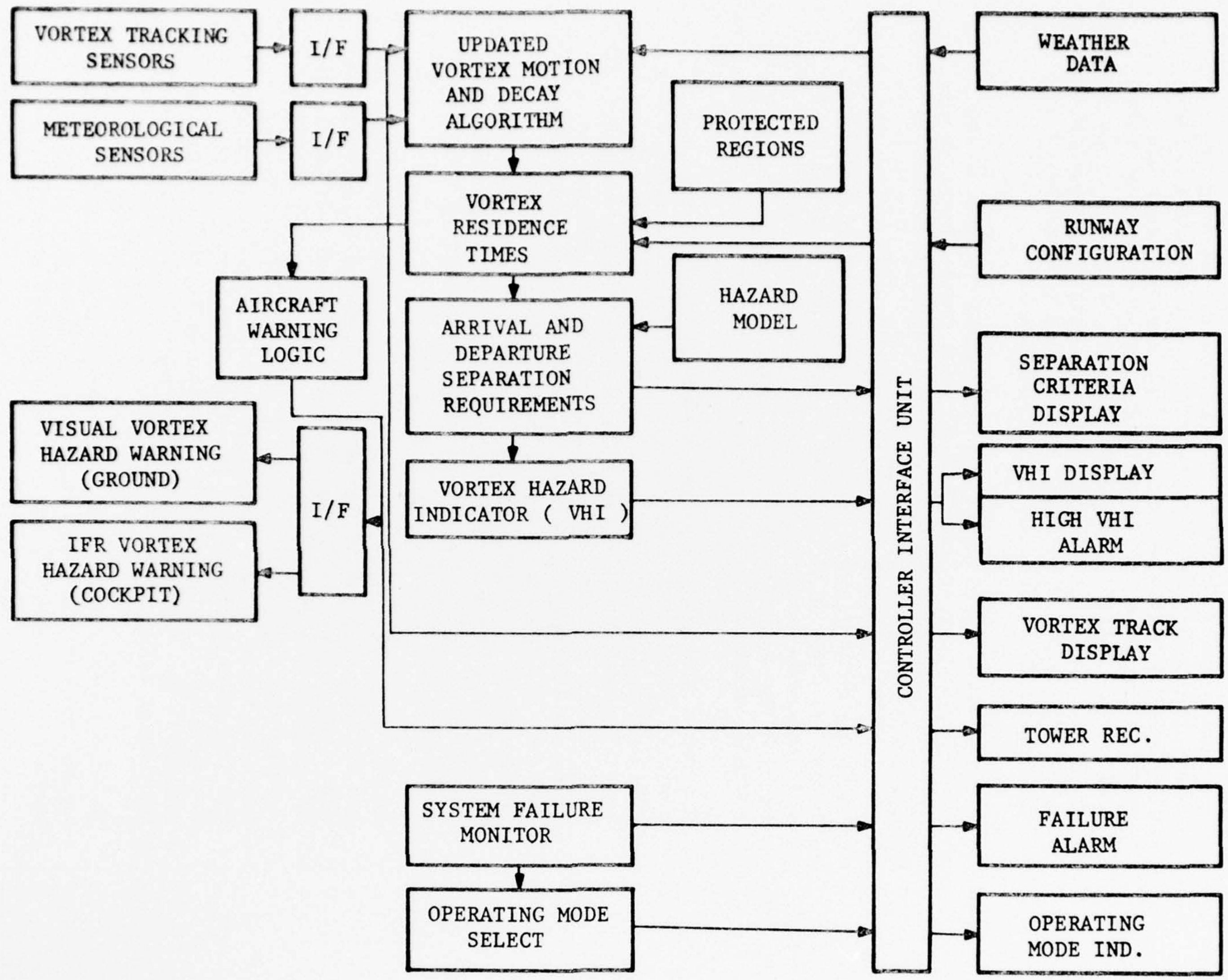

Figure 3-5. Block Diagram of A Wake Vortex Avoidance System.

and vortex position as a function of time relative to the lead aircraft could be monitored by the sensing subsystem. The rate of motion of the vortex from the vortex tracker and the rate of decay of the vortex would be inputs to an algorithm to determine when the approach corridor would be clear relative to the avoidance of the vortex shed by the lead aircraft. The controller or the M&S system would compare this time with the time of arrival of the aircraft of concern over the middle marker to determine if corrective action is necessary. In the interim, the vortex position and decay as a function of time have been fed back to the predictive model as a corrective or updating input. The actual vortex behavior would then be compared in the model with the predicted behavior to determine if any update or correction is necessary, thus providing a completely automatic closed-loop system for providing positive vortex avoidance.

The type of data and format to be provided to the approach or tower controller would be determined during system design and the interface simulation and testing with terminal automation through laboratory and field tests. The major consideration is making the derived data simple, timely and compatible with ATC procedures, yet totally effective for both the determination of aircraft separation and the provision of avoidance direction should the need arise.

3.3.2 Safety Considerations

Although the basic objective of the WVAS development is concerned with airport capacity increases, it is inherent to any systems development that safety remain the primary consideration in operational application. In conjunction with both feasibility and operational suitability testing, detailed and comprehensive analyses will be completed on the safety aspects of operational implementation of candidate systems. To support these analytical efforts a rigorous data collection program will be initiated parallel with the theoretical work. The driving factors in acquiring substantiating data on vortex behavior and effects are: an overall statistically valid data base; a complete assessment of aircraft types; and as broad a spectrum of atmospheric conditions as is reasonably possible. All safety findings will be incorporated in the final recommendations submitted to the Operating Services for system implementation.

3.4 Predictive Model

Any wake vortex avoidance strategy depends on the ability to predict vortex behavior as aircraft separations must be established at some distance from the airport. The prediction may be done in an "a priori" sense; as in the VAS where extensive data have shown that if the current wind is outside the ellipse then one may "predict" that vortices will not be hazardous at 3-mile spacings. A truly predictive system should allow adaptive separations; it would minimize the conservativeness of the VAS and should allow further lowering of separations below 3 nautical miles.

The development of the full predictive model will encompass seven stages: (1) a mathematical model of vortex behavior must be formulated using aeordynamic and fluid mechanic principles; (2) the resulting model must be checked by conducting a series of controlled flight tests; (3) the model must be refined to account for deviations between model and flight test data; (4) the model must be statistically verified under operational airport conditions using measured vortex data; (5) the forecasting requirements of the model inputs must be established; (6) the model must be adapted to a minicomputer (or microprocessor, if possible); and (7) the model must be verified under operational conditions. To date, the predictive model effort has progressed through the first three stages and will complete the fourth stage during FY 1979. Stages 5, 6, and 7 will be completed in early FY-1980.

3.4.1 Early Predictive Model

The predictive model describes the transport and behavior of aircraft wakes using the mechanisms of wind, wind shear, ground plane, buoyancy and decay. Only the average motion of the vortices is considered, not the fine-scale motion affected by atmospheric inhomogeneities. The load distribution of a wing defines all the properties of the inviscid vortex development; however, during the first stage of the development of the transport function for the predictive model, the assumption of an organized vortex pair motion was made. The pair moves in its induced field causing the vortices to propagate downward with a velocity directly proportional to the aircraft lift coefficient and velocity and inversely proportional to the aspect ratio. Stage 1 has been completed and represents a composite of tasks performed by TSC, AeroVironment and Lockheed-Huntsville.

3.4.2 Controlled Flight Tests

A series of flight tests was conducted to verify the early predictive model using B-747, B707, CV-880, and DC-6 aircraft (over 400 flybys). Both the motion of the vortices and the meteorological conditions were recorded. The tests were performed at the National Aviation Facilities Experimental Center.

Vortex Tracks were recorded photographically and by ground-wind sensors. NAFEC has a 150-ft. tower instrumented with hot-wire anemometers, colored smoke dispensers at 20-ft. intervals, and meteorological instrumentation at five levels. Smoke was used to visualize the vortices. A 35-mm camera was positioned 2000 ft. from the tower aligned with the prevailing wind direction. Photographs were taken every second and the vortex tracks were obtained by examining each photo and locating the vortices by scaling photographic distances with known distances. Gill single-axis propeller anemometers were arrayed on a base-line near the 150-ft. tower to measure the wind component perpendicular to the aircraft flight path. As a vortex moved through the anemometer system, it produced a distinctive signature superimposed upon the background wind. The testing associated with Stage 2 was completed in November 1972 and the data analysis was completed in April 1974.

3.4.3 Updated Predictive Model

Deviations were noted between predicted vortex tracks and the actual tracks recorded during the controlled flight tests. The mechanisms were identified and included in a revised or updated predictive model.

3.4.4 Operational Check

In 1974, TSC began extensive tests at the Kennedy International Airport. The approach zone of runway 31R was equipped with a number of vortex tracking systems (a pulsed bistatic acoustic system, a CW bistatic/monostatic acoustic system, three ground-wind systems similar to the one used in the NAFEC tests, and two CW CO_2 laser Doppler systems). The objectives of the test program were the evaluation of the vortex sensors and the validation of the vortex transport and lifetime models for forecasting the behavior of the vortex wakes. A network of tower-mounted meteorological sensors was used to continuously monitor the three components of the wind, turbulence, temperature, and humidity.

Comparative plots of predicted vortex position and measured vortex locations by all sensors was completed under contract by Lockheed Research and Engineering of Huntsville, Alabama. This analysis consists of 2000 aircraft landings to define predictive accuracy.

Vortex and meteorological data collected from Kennedy are now being analyzed to also define the final operational requirements for the predictive model. The study is scheduled to be completed in December 1977. A separate study is being conducted on the decay of vortices near the ground. Decay models will be available by June 1979.

3.4.5 Forecasting

The previous tasks bring together the means for predicting how vortices will behave (both transport and decay) given the ambient meteorological conditions. Since separations are often established up to 15 minutes before an aircraft actually touches down, techniques must be developed to forecast the critical weather factors at least 15 minutes in advance. The task is primarily meteorological in nature but it must be noted that the actual airport weather conditions are not being forcast, only the response of wake vortices to these conditions. The task does require the prediction of the short-term stability of meteorological conditions, primarily wind direction and speed in the approach corridor. It is anticipated that most of the work will be completed during FY 1980.

3.4.6 Programming

The forecasting function must be combined with the other functions of the vortex predictive model (transport and decay) and reduced for use in a minicomputer (or microprocessor, if possible). Most of this work will be done in-house by TSC and be completed in early FY 1980.

3.4.7 Operational Test

The final version of the predictive model will then need to be tested in an operational environment. The Chicago O'Hare test site would be ideal for this test which should be conducted for at least six months. The data analysis would be done at TSC but the tests would be run by a field site contractor. The final output would consist of the model itself along with the necessary specifications on the required input data. The task could be completed during FY 1980.

3.5 Other Major Activities

3.5.1 Toronto International Airport - Departure Vortex Measurements

The FAA entered into a joint project with the Canadian Ministry of Transport (MOT) in a cooperative R&D wake vortex measurement program. The purpose of the program is to acquire takeoff vortex behavior data measured by acoustic, ground-wind, laser and meteorological sensors and to use this data base to verify and update the predictive vortex behavior model. As a secondary objective, the data will be analyzed to determine if an algorithm can be developed that could be applied to the VAS to allow reduced departure separations during specific meteorological condtions.

TSC was directed by the FAA to provide: the technical equipment and assist MOT personnel in its installation; equipment checkout and the training of the MOT technical personnel in its operation and maintenance; data reduction and analysis; and periodic reports on the results of the measurements as well as logistic support for the test site during its operation. The MOT provided the personnel for the site installation, equipment operation and maintenance, and funds for a portion of the data processing and analysis.

The departure vortex measurements are being made along the 05R end of Runway 05R-23L at the Toronto International Airport, Toronto, Canada, as shown in Figure 2-6. Three baselines were installed perpendicular to the runway centerline.

(a) One baseline, 3700 ft. from the 05R threshold consists of a Ground-Wind Vortex Sensing System.

(b) One baseline, 2700 ft. from the 05R threshold consists of a Ground-Wind Vortex Sensing System and a Monostatic Acoustic Vortex Sensing System and a camera.

(c) One baseline, 1200 ft. from the 05R threshold consists of a Ground-Wind Vortex Sensing System.

The Ground-Wind Vortex Sensing System utilizes Gill-type anemometers to determine lateral vortex strength as a function of time and the camera is utilized to determine aircraft departure profiles. In addition, a set of meteorological sensors (anemometers and thermistors) are installed on an existing 100 ft. waveguide antenna. All electronics are housed in a shelter at the base of the waveguide antenna.

The data are recorded automatically via magnetic tape recorders located in the instrumentation shelter. In addition, an operator maintains a log into which he enters the date, aircraft type, time of passage abeam the instrumentation, general meteorological conditions and any unusual events.

The data tapes and operators log sheets are shipped to TSC where the data are processed and analyzed to provide individual takeoff vortex tracks giving the lateral position and the strength of the vortex as a function of time for each aircraft passage. The tracks are correlated with the meteorological conditions measured during the time of aircraft passage. The tracks are categorized by aircraft type and meteorological conditions and histograms established for each aircraft type as well as for specific ranges of total wind, cross-wind, turbulence and atmoshperic stability. These measured values will be compared to the predictive vortex takeoff model and used to refine the model. All tracks will be maintained in a total vortex data base for future use.

A final summary report will be prepared and distributed by TSC upon mutual agreement by the FAA and the MOT on the content of the report. The current measurement program completed a six-month test phase and the FAA and MOT agreed upon a six month extension in order to obtain a statistically significant sample of data and to resolve some unanticipated vortex behavior which was identified in the early data collection. Instrumentation changes were implemented to fulfill these latter objectives. This joint FAA/MOT test terminated October 1, 1977.

3.5.2 Applicability of VAS Separations to Departing Aircraft

The primary consideration in the development of the Vortex Advisory System was its operational application in the arrival mode only. Initial system design did not involve VAS applicability to the take-off situation. Preliminary research assessing the behavior of vortices generated by departing aircraft has indicated that it is feasible to pursue the development of a wind criterion algorithm to be used for establishing departure intervals. This algorithm would be similar to the present VAS algorithm used for arrivals.

Capacity gains realized through VAS operations could possibly be significantly increased by extending VAS separations to departing aircraft as well. Like arrival separations, departure separations would be reduced only during periods when the ambient winds meet the criteria established in the wind criterion algorithm.

The joint program with the Canadian MOT (discussed in the preceding section) was the initial research effort for expanding VAS applicability to departures. The vortex data base acquired at the Toronto test site, though adequate for gauging preliminary trend information on vortex behavior and decay, was not extensive enough to statistically derive and validate an algorithm based on the characteristics of the wake vortex generated by departing aircraft. Further data collection efforts will be required to establish the statistical validity of VAS separations for departures and thoroughly analyze all operational safety factors involved in decreasing the current departure standards.

FAA currently has a research facility capable of acquiring and analyzing vortex strength, transport, and decay measurements for arrivals and departures. A laser Doppler velocometer (LDV), housed in a self-propelled vehicle with full data acquisition and processing capability has been developed. This mobile LDV van has been used in field tests at Logan and O'Hare International Airports.

The operational evaluation of the O'Hare VAS installation will be completed in mid-1978. Based on the final assessment of VAS impact on arrival capacity and delay rates, a more knowledgable decision for incorporating VAS operations in the departure situation can then be made. Pending the establishment of a definitive operational requirement for departure VAS operations, the program office will continue the planning of departure data collection efforts. Preliminary planning, including fiscal support, for continued data collection with the LDV is complete through FY-1978. Philadelphia International Airport would be the logical site for further departure data collection since the runway configuration would readily support the installation of the measurement system previously installed at Toronto International Airport. The aircraft mix and prevailing meteorology would provide the wind measurements necessary to evaluate the wind condition/vortex behavior correlation required to contract the VAS departure algorithm. The LDV data collection and installation of the measurement system will be accomplished primarily as a TSC in-house effort with minimal contractor support.

Additionally, the installation of a vortex data collection system at Phaladelphia IAP, because of its proximity to NAFEC, would permit maximum utilization of NAFEC in-house resources in operating and maintaining the site during data collection projects.

3.6 Program Products

Current planning calls for the Wake Vortex Avoidance System program products to take two forms: a prototype Wake Vortex Avoidance System and the associated technical data package including all computer software. Final products will be reviewed and approved by FAA's Associate Administrator for Engineering and Development prior to hand-off to the appropriate Operating Services. In the case of the Wake Vortex Avoidance System, the end products impact Air Traffic and Airways Facilities Service from both hardware and procedural aspects and Flight Standards Service in the operational procedures and safety areas.

Supporting technical data and systems analyses will be published as FAA reports as authorized by the offices of the Associate Administrator for Engineering and Development and Director of the Systems Research and Development Service. These reports will be available to the Operating Services responsible for development of the operational implementation strategy.

4.0 Funding Requirements

The resources required for the Wake Vortex Program are shown in Table 4-1. Resources noted in Table 4-1 reflect best current estimates based on the program described in this document.

TABLE 4-1. WAKE VORTEX PROGRAM FUNDING ($000)
PROGRAM CODE: 084-452.

FY 1976-1977 FUNDING:

FISCAL YEAR	1976	1976T	1977	TOTAL
IN-HOUSE	1435	299	1342	3076
CONTRACT	1013	287	330	1630
TOTALS	2448	586	1672	4706

CURRENT YEAR BREAKOUT:

FISCAL YEAR	1978					
SUBPROGRAM TITLE	W.O.		NAFEC		TSC	
	I/H	CONT.	I/H	CONT.	I/H	CONT.
VORTEX ADVISORY SYSTEM	–	125	390	–	557	50
WAKE VORTEX AVOIDANCE SYSTEM	–	–	76	–	–	175
WVAS PREDICTIVE MODELING	–	–	–	–	140	25
VORTEX ALLEVIATION RESEARCH	–	–	–	–	–	–
SUBTOTALS		125	466	–	697	250
COMBINED PROGRAM						
IN-HOUSE	1163					
CONTRACT	375					
TOTAL	1538					

FUTURE REQUIREMENTS:

FISCAL YEAR	1979	1980	1981	1982	1983	TOTAL
PROGRAM TOTALS	750	1800	1800	1000	1000	6350

NOTES: AVAILABILITY OF ESTIMATED FUNDS IS SUBJECT TO OST/OMB CONGRESSIONAL ACTIONS.
FUNDING ESTIMATES REFLECT PLANNED PROGRAM MILESTONES SUBJECT TO AVAILABILITY OF FUNDS.
CURRENT YEAR ESTIMATES ARE CONSISTENT WITH WAKE VORTEX ADVISORY/AVOIDANCE SYSTEMS FISCAL PROGRAM.

5.0 Program Management

The System Research and Development Service has overall responsibility for program management. The Approach and Landing Division (ARD-700) is the lead operating division in SRDS responsible for the conduct and accomplishment of engineering and development efforts commensurate with FAA and E&D management policies and direction. Effective management of this program requires the coordinated efforts of other government organizations, contractors, and the internal offices of the Federal Aviation Administration.

5.1 Systems Research and Development Service, Approach and Landing Division, Wind Shear/WVAS Branch, ARD-740.

ARD-740 will be responsible for the direct program management, effect coordination with other SRDS offices, and establish requirements for supporting subprogram efforts within and external to the FAA. The Branch Chief is responsible for defining program activities, negotiating coordinated support and participation of other government functions, monitoring contractor activities, establishing realistic program milestones and schedules, and planning and controlling funding requirements to meet program objectives. The Branch will act as the SRDS central point of contact for FAA Operating Services and serve as the Contracting Officer's Technical Representative for contracts issued by the Branch. The Branch Chief also serves as co-chairman of the FAA/NASA Wake Vortex Alleviation Research Steering Group. This working group insures coordination of the activities in joint FAA/NASA wake vortex research efforts. This office is responsible for insuring FAA senior management is kept aware of program status, problem areas, and planned program requirements.

5.2 Transportation Systems Center, Traffic and Operations Branch, TSC-521

TSC-521, under the policy and fiscal direction of the FAA, is responsible for detailed system design and development, sensor technology development, software development, and systems integration analyses required for the design, development, testing, and prototyping of the Wake Vortex Avoidance System (WVAS) in accordance with the approved FAA Engineering and Development Program Plan. TSC-521 will exercise responsibility for contracted efforts by establishing Work Statements, Requests for Proposals, and selection of contractors supporting TSC program areas. TSC-521 will, under the direction of SRDS and as required by the FAA Operating Services, act as a technical advisor during the implementation and deployment of the Wake Vortex Avoidance System. TSC-521 is responsible for the development of system specifications, technical drawings and diagrams, functional descriptions, recommended maintenance procedures, installation and check-out guides required for the completed Technical Data Package.

5.3 National Aviation Facilities Experimental Center (NAFEC), Aircraft and Airports Safety Division, ANA-400

ANA-400 will be responsible for the planning and direct support of the operational field testing and evaluation of the prototype equipments and other field or flight tests applicable to WVAS development. They will assist with the development and execution of test plans, provide reliability and maintainability assessments, and human factors studies, as required, in the operational test and evaluation and demonstration of the WVAS. They will employ the unique capabilities of the experimental center in simulation and automated data processing to support program objectives. ANA-400 will be responsible for providing appropriate status reports and documentation to SRDS management.